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Proton-deuteron asymmetry in Drell-Yan processes and polarized light-antiquark distributions

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ABSTRACT

We discuss the relation between the ratio of the proton-deuteron (pd) Drell-Yan cross section to the proton-proton (pp) one $\Delta_{(T)}\sigma_{pd}/2\Delta_{(T)}\sigma_{pp}$ and the flavor asymmetry in polarized light-antiquark distributions. Using a recent formalism of the polarized pd Drell-Yan process, we show that the difference between the pp and pd cross sections is valuable for finding not only the flavor asymmetry in longitudinally polarized antiquark distributions but also the one in transversity distributions. It is especially important that we point out the possibility of measuring the flavor asymmetry in the transversity distributions because it cannot be found in W production processes and inclusive lepton scattering due to the chiral-odd property.

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1 Introduction

Unpolarized parton distributions are now well known with various lepton and hadron scattering data. We also have a rough idea on the longitudinally polarized ones with many experimental data on the g_1 structure function [1]. However, the details of the polarized distributions are not known yet. For example, the polarized light-antiquark distributions are assumed to be flavor symmetric although the flavor asymmetric sea is confirmed in the unpolarized case [2]. The unpolarized asymmetry was first revealed by the New Muon Collaboration (NMC) [3] in the failure of the Gottfried sum rule, which was studied in muon deep inelastic scattering experiments. It was then confirmed by the CERN-NA51 [4] and Fermilab-E866 [5] collaborations in Drell-Yan experiments. Furthermore, the HERMES semi-inclusive data [6] indicated a similar flavor asymmetry. In this way, the $\bar{u}/\bar{d}$ asymmetry is now an established fact. It is also theoretically understood that various factors contribute to the asymmetry [2]. They include non-perturbative mechanisms such as meson clouds and the exclusion principle. Although the effect may not be large, there could be also a perturbative contribution.

In order to determine the major mechanism for creating the asymmetry, other observables should be investigated. The flavor asymmetries in longitudinally-polarized and transversity distributions are appropriate candidates for the observables in the light of the Relativistic Heavy Ion Collider (RHIC) SPIN project and others. There are also some model studies on the possible antiquark flavor asymmetry [7]. Because the g_1 data are not enough to find the asymmetry, we should reply on semi-inclusive or hadron-scattering ones. For example, charged-hadron production data are valuable. However, the Spin Muon Collaboration (SMC) and HERMES data are not accurate enough at this stage for finding a small effect although an analysis suggests a slight $\Delta\bar{u}$ excess over $\Delta\bar{d}$ [8]. There is another possibility of studying it at RHIC by W production processes. It has been already shown [9, 10] that the W charge asymmetry is very sensitive to the antiquark flavor asymmetry in the proton-proton (pp) reaction. On the other hand, the disadvantage of the W production is that the asymmetry in the transversity distributions cannot be investigated because of the chiral-odd nature [11]. Therefore, we need to find an alternative method.

This is one of our major purposes for investigating the polarized proton-deuteron (pd) Drell-Yan processes. An alternative way is to combine the pd Drell-Yan data with the pp data as it has been done in the unpolarized case [4, 5]. However, the formalism of the polarized pd Drell-Yan had not been available until recently. In particular, it was not obvious how the additional tensor structure is involved in the polarized cross sections because the deuteron is a spin-1 hadron. References [12, 13] made it possible to address ourselves to the polarized pd processes. Taking advantage of the formalism, we can discuss the possibility of measuring the polarized flavor asymmetry by combing the pd Drell-Yan data with the pp ones. Although such an idea was already pointed out in Refs. [12, 13], the purpose of this paper is to show the actual possibility by numerical analyses. The relation between the polarized pd Drell-Yan cross section and

the flavor asymmetry is discussed in Sec. 2. Then, numerical results are explained in Sec. 3, and conclusions are given in Sec. 4.

2 Flavor asymmetry in polarized proton-deuteron Drell-Yan processes

Although the lepton scattering suggests the asymmetry $\bar{u}/\bar{d} \neq 1$ in the failure of the Gottfried sum rule, it does not enable us to determine the x dependence. Therefore, the pd Drell-Yan process ($p+d \to \mu^+\mu^- + X$) has been used for measuring the unpolarized $\bar{u}/\bar{d}$ ratio in combination with the pp Drell-Yan. Another possibility is to use the W production processes [10]. We discuss a method of using the pd Drell-Yan process for finding the polarized flavor asymmetry in this section.

There are at least two complexities in handing the deuteron reaction. First, the deuteron is a spin-1 hadron so that additional spin structure exists. This point is clarified in Refs. [12, 13], so that the interested reader may read these papers for the details. Second, the deuteron structure functions are not simple summations of proton and neutron ones because of nuclear effects. Although such nuclear corrections are important for a precise analysis, we do not address ourselves to them in this paper because nuclear modification does not affect major consequences of this paper. If experimental data are taken in future, shadowing, D-state admixture, and Fermi-motion corrections [14] should be taken into account for detailed comparison.

We found in Ref. [12] that the difference between the longitudinally-polarized pd cross sections is given by

$$\Delta\sigma_{pd} = \sigma(\uparrow_L, -1_L) - \sigma(\uparrow_L, +1_L) \propto -\frac{1}{4}\left[2\,V_{0,0}^{LL} + (\frac{1}{3} - cos^2\theta)\,V_{2,0}^{LL}\right] , \qquad (1)$$

where the subscripts of $\uparrow_L$, $+1_L$, and -1_L indicate the longitudinal polarization and $\sigma(pol_p, pol_d)$ indicates the cross section with the proton polarization pol_p and the deuteron one pol_d. The longitudinally polarized structure functions $V_{0,0}^{LL}$ and $V_{2,0}^{LL}$ are defined in Ref. [12]. The subscripts ℓ and m of the expression $V_{\ell,m}^{LL}$ indicate that it is obtained by the integration $\int d\Omega\, Y_{\ell m}\, \Delta\sigma_{pd}$, and the superscript $L\,L$ means that the proton and deuteron are both longitudinally polarized. The θ is the polar angle of the lepton μ^+. A parton model should be used for discussing relations between the structure functions and parton distributions. In the following, we take the expression which is obtained by integrating the cross section over the virtual-photon transverse momentum $\vec{Q}_T$. According to Ref. [13], it is given by

$$\Delta\sigma_{pd} \propto \sum_a e_a^2 \left[\, \Delta q_a(x_1)\, \Delta\bar{q}_a^d(x_2) + \Delta\bar{q}_a(x_1)\, \Delta q_a^d(x_2) \,\right] , \qquad (2)$$

where Δq_a^d and $\Delta\bar{q}_a^d$ are the longitudinally-polarized quark and antiquark distributions in the deuteron. The subscript a indicates quark flavor, and e_a is the corresponding

quark charge. The momentum fractions are given by $x_1 = \sqrt{\tau}e^{+y}$ and $x_2 = \sqrt{\tau}e^{-y}$ with $\tau = M_{\mu\mu}^2/s$ and the dimuon rapidity $y = (1/2)\ln[(E^{\mu\mu} + P_L^{\mu\mu})/(E^{\mu\mu} - P_L^{\mu\mu})]$ in the case of small P_T. We neglect the nuclear corrections in the deuteron and assume isospin symmetry, so that the distributions in the deuteron become

$$\begin{aligned} &\Delta u^d = \Delta u + \Delta d, \quad \Delta d^d = \Delta d + \Delta u, \quad \Delta s^d = 2\Delta s, \\ &\Delta \bar{u}^{\,d} = \Delta \bar{u} + \Delta \bar{d}, \quad \Delta \bar{d}^{\,d} = \Delta \bar{d} + \Delta \bar{u}, \quad \Delta \bar{s}^{\,d} = 2\Delta \bar{s}. \end{aligned} \tag{3}$$

The polarized gluon distribution does not contribute to our LO analysis. Even in the NLO studies, its effect is rather small in the small-P_T region which is investigated in this paper, whereas it contributes significantly to large-P_T cross sections. Estimates of such gluon contributions are discussed in Ref. [15].

The situation is slightly different in the transversity case. If the cross-section difference is simply given by $\Delta_T\sigma_{pd} = \sigma(\phi_p = 0, \phi_d = 0) - \sigma(\phi_p = 0, \phi_d = \pi)$, where ϕ is the azimuthal angle of a polarization vector, four structure functions ($V_{0,0}^{TT}$, $V_{2,0}^{TT}$, $U_{2,2}^{TT}$, and $U_{2,1}^{UT}$) contribute. Here, the superscript UT, for example, indicates that the proton is unpolarized and the deuteron is transversely polarized. However, the parton model with the $\vec{Q}_T$ integration suggests that only $U_{2,2}^{TT}$ remains finite and higher-twist functions vanish [13]. In the following discussions, we completely neglect the higher-twist contributions. Then, the cross-section difference is given in the parton model as

$$\begin{aligned} \Delta_T\sigma_{pd} &= \sigma(\phi_p = 0, \phi_d = 0) - \sigma(\phi_p = 0, \phi_d = \pi) \\ &\propto \sum_a e_a^2 \left[\Delta_T q_a(x_1)\, \Delta_T \bar{q}_a^d(x_2) + \Delta_T \bar{q}_a(x_1)\, \Delta_T q_a^d(x_2) \right] , \end{aligned} \tag{4}$$

where $\Delta_T q$ and $\Delta_T \bar{q}$ are quark and antiquark transversity distributions. The nuclear corrections are again neglected in the parton distributions of the deuteron, so that the equations corresponding to Eq. (3) are used in the following analysis.

The pp cross sections are given in the same way simply by replacing the parton distributions in Eqs. (2) and (4): $q^d \to q$ and $\bar{q}^{\,d} \to \bar{q}$. The ratio of the pd cross section to the pp one is then given by

$$R_{pd} \equiv \frac{\Delta_{(T)}\sigma_{pd}}{2\,\Delta_{(T)}\sigma_{pp}} = \frac{\sum_a e_a^2 \left[\Delta_{(T)} q_a(x_1)\, \Delta_{(T)} \bar{q}_a^d(x_2) + \Delta_{(T)} \bar{q}_a(x_1)\, \Delta_{(T)} q_a^d(x_2) \right]}{2 \sum_a e_a^2 \left[\Delta_{(T)} q_a(x_1)\, \Delta_{(T)} \bar{q}_a(x_2) + \Delta_{(T)} \bar{q}_a(x_1)\, \Delta_{(T)} q_a(x_2) \right]} , \tag{5}$$

where $\Delta_{(T)} = \Delta$ or Δ_T depending on the longitudinal or transverse case. At large $x_F = x_1 - x_2$, the $\Delta_{(T)}\bar{q}_a(x_1)$ terms can be neglected, so that the ratio becomes

$$R_{pd}(x_F \to 1) = 1 - \frac{\left[\, 4\,\Delta_{(T)} u_v(x_1) \,-\, \Delta_{(T)} d_v(x_1) \,\right] \left[\, \Delta_{(T)} \bar{u}(x_2) - \Delta_{(T)} \bar{d}(x_2) \,\right]}{8\,\Delta_{(T)} u_v(x_1)\, \Delta_{(T)} \bar{u}(x_2) \,+\, 2\,\Delta_{(T)} d_v(x_1)\, \Delta_{(T)} \bar{d}(x_2)} , \tag{6}$$

where $x_1 \to 1$ and $x_2 \to 0$. If the distribution $\Delta_{(T)}\bar{u}$ is the same as $\Delta_{(T)}\bar{d}$, the ratio is simply given by

$$R_{pd}(x_F \to 1) = 1 \quad \text{if } \Delta_{(T)}\bar{u} = \Delta_{(T)}\bar{d} \, . \tag{7}$$

Equation (6) shows that the deviation from one is directory proportional to the $\Delta_{(T)}\bar{u} - \Delta_{(T)}\bar{d}$ distribution. If the valence-quark distributions satisfy $\Delta_{(T)}u_v(x \to 1) \gg \Delta_{(T)}d_v(x \to 1)$ [16], Eq. (6) becomes

$$R_{pd}(x_F \to 1) = 1 - \left[\frac{\Delta_{(T)}\bar{u}(x_2) - \Delta_{(T)}\bar{d}(x_2)}{2\,\Delta_{(T)}\bar{u}(x_2)} \right]_{x_2 \to 0} = \frac{1}{2} \left[1 + \frac{\Delta_{(T)}\bar{d}(x_2)}{\Delta_{(T)}\bar{u}(x_2)} \right]_{x_2 \to 0} . \quad (8)$$

Therefore, if the $\Delta_{(T)}\bar{u}$ distribution is negative as suggested by the recent parametrizations and if the $\Delta_{(T)}\bar{u}$ distribution is larger (smaller) than $\Delta_{(T)}\bar{d}$, the ratio is larger (smaller) than one. However, if the $\Delta_{(T)}\bar{u}$ distribution is positive, it is a different story. In this way, we find that the data in the large-x_F region are especially useful in finding the flavor asymmetry ratio $\Delta_{(T)}\bar{u}(x)/\Delta_{(T)}\bar{d}(x)$.

On the other hand, the other x_F regions are not so promising. For example, if another limit $x_F \to -1$ is taken, the ratio is

$$R_{pd}(x_F \to -1) = \frac{[\,4\,\Delta_{(T)}\bar{u}(x_1) + \Delta_{(T)}\bar{d}(x_1)\,]\,[\,\Delta_{(T)}u_v(x_2) + \Delta_{(T)}d_v(x_2)\,]}{8\,\Delta_{(T)}\bar{u}(x_1)\,\Delta_{(T)}u_v(x_2) + 2\,\Delta_{(T)}\bar{d}(x_1)\,\Delta_{(T)}d_v(x_2)} , \quad (9)$$

where $x_1 \to 0$ and $x_2 \to 1$. If the condition $\Delta_{(T)}u_v(x \to 1) \gg \Delta_{(T)}d_v(x \to 1)$ is satisfied, the ratio becomes

$$R_{pd}(x_F \to -1) = \frac{1}{2} \left[1 + \frac{\Delta_{(T)}\bar{d}(x_1)}{4\,\Delta_{(T)}\bar{u}(x_1)} \right]_{x_1 \to 0} . \quad (10)$$

If the antiquark distributions are same, the ratio is given by $R_{pd} = 5/8 = 0.625$. Comparing the above equation with Eq. (8), we find the difference of factor 4. It suggests that the ratio R_{pd} is not as sensitive as the one in the large-x_F region although the $\Delta_{(T)}\bar{u}/\Delta_{(T)}\bar{d}$ asymmetry could be found also in this region.

The pd/pp ratio has been used for finding the flavor asymmetry $\bar{u}/\bar{d}$ in the unpolarized reaction [4, 5]. In this paper, we would like to show the possibility of finding it in the polarized parton distributions. Our investigation is particularly important for the transversity distributions. In finding the flavor asymmetry in the unpolarized and longitudinally-polarized distributions, popular ideas are to use inclusive lepton scattering and W production data. However, these methods cannot be used for the transversity distributions because of the chiral-odd property. The pd asymmetry in the transversely-polarized Drell-Yan processes enables us to determine the flavor asymmetry $\Delta_T\bar{u}/\Delta_T\bar{d}$.

3 Results

We show expected pd/pp ratios numerically in this section by using recent parametrizations for the polarized parton distributions. First, the leading-order (LO) results are shown in Fig. 1 at $\sqrt{s} = 50$ GeV and $M_{\mu\mu} = 5$ GeV. The Drell-Yan cross-section ratio

R_{pd} is calculated in the longitudinally- and transversely-polarized cases, and the results are shown by the solid and dashed curves, respectively. The longitudinally-polarized distributions are taken from the 1999 version of the LSS (Leader-Sidorov-Stamenov) parametrization [17]. Strictly speaking, their distributions cannot be used in the LO analysis because they are provided at the NLO level. Nevertheless, the same input distributions are used in our LO analysis in order to compare with the next-to-leading-order (NLO) evolution results in the following. The flavor asymmetry ratio is taken as

$$r_{\bar{q}} \equiv \frac{\Delta_{(T)}\bar{u}}{\Delta_{(T)}\bar{d}} = 0.7,\ 1.0,\ \text{or } 1.3, \tag{11}$$

at Q^2=1 GeV^2. Because the input distributions are provided at Q^2=1 GeV^2, they should be evolved to those at $Q^2 = M_{\mu\mu}^2$ with the LO evolution equations [18] for the longitudinally-polarized and transversity distributions. Although the longitudinal distributions are roughly known from the g_1 data, there is no experimental information on the transversity ones. Because nonrelativistic quark models indicate that they are equal to the longitudinal ones, we assume the same LSS99 distributions at the initial point Q^2 = 1 GeV^2. If the antiquark distributions are flavor symmetric ($r_{\bar{q}}$=1), the pd/pp ratio satisfies the conditions, $R_{pd} \to 1$ as $x_F \to 1$ and $R_{pd} \to 0.625$ as $x_F \to -1$. The flavor-asymmetry effects are conspicuous especially at large x_F as we explained in Sec. 2. Because the $\Delta_{(T)}\bar{u}$ distribution is negative in the used LSS99 parametrization, the ratio R_{pd} is larger than one at large x_F if there exists a $|\Delta_{(T)}\bar{d}|$ excess over $|\Delta_{(T)}\bar{u}|$ ($r_{\bar{q}}$=0.7). On the other hand, if $|\Delta_{(T)}\bar{u}|$ is larger than $|\Delta_{(T)}\bar{d}|$ ($r_{\bar{q}}$=1.3), it is smaller than one. In the small-x_F region, the flavor-asymmetry contributions are not so large due to the suppression factor 1/4. It is also interesting to find that there is almost no difference between the longitudinally- and transversely-polarized ratios if the initial distributions are identical.

Next, we show NLO evolution results in Fig. 2. Using the same LSS99 distributions at Q^2=1 GeV^2, we evolve them to the distributions at Q^2=25 GeV^2 by the NLO longitudinal and transversity evolution equations [18]. As shown in the figure, the calculated ratios are almost the same as those of the LO. However, there are slight differences as it is noticeable in the large-x_F region: the ratio R_{pd} is not equal to one although the antiquark distributions are flavor symmetric at Q^2=1 GeV^2. It is because the Q^2 evolution gives rise to the asymmetric sea [2, 18] although the initial distributions are flavor symmetric. This kind of perturbative QCD effect is not so large in the evolution from Q^2=1 GeV^2 to 25 GeV^2. If the distributions are evolved from the GRSV (Glück-Reya-Stratmann-Vogelsang) [19] type small Q^2, the effect is larger. The comparison of Fig. 2 with Fig. 1 indicates that the NLO analysis is important for a precise determination of the $\Delta_{(T)}\bar{u}/\Delta_{(T)}\bar{d}$ ratio from measured experimental data.

In Fig. 3, the dependence on the center-of-mass energy $\sqrt{s}$ is shown. The LO cross-section ratio is calculated at the RHIC energies $\sqrt{s}$=200 and 500 GeV. The calculated ratios are almost equal to those at $\sqrt{s}$=50 GeV in the large and small x_F

regions. However, the ratio becomes a steeper function of x_F as $\sqrt{s}$ increases, so that intermediate-x_F results depend much on the c.m. energy. In other words, the intermediate region is sensitive to the details of the parton distributions.

Finally, we discuss parametrization dependence. A difference from the unpolarized ratio is that the distributions $\Delta_{(T)}q$ and $\Delta_{(T)}\bar{q}$ could be negative so that the denominator, for example in Eq. (5), may vanish depending on the kinematical condition. If this is the case, the ratio has strong x_F dependence in the intermediate region. Therefore, we should be careful that the obtained numerical results could change significantly depending on the choice of the input polarized parton distributions. In particular, the x dependence of the antiquark distributions, needless to say for the gluon distribution, is not well known although $\Delta\bar{q}$ seems to be negative and $|\Delta\bar{q}|$ is rather small according to the recent parametrizations [1, 17, 19, 20].

The LSS99 distributions have been used so far in our analysis. There are several other polarized parametrizations. In order to show the dependence on the used parametrization, we employ the Gehrmann-Stirling set A (GS-A NLO) [20] and the GRSV96 (NLO) [19]. The calculated LO ratios are shown in Fig. 4. The GS-A and GRSV96 distributions are calculated first at Q^2=1 GeV^2 by their own programs. Then, a certain antiquark ratio $r_{\bar{q}}$ is introduced. After this prescription, the distributions are evolved to Q^2=25 GeV^2 by the programs in Ref. [18]. The calculated results are not much different between the LSS99 and GRSV parametrizations. However, if the GS-A distributions are used, the results are much different. This is because the GS-A antiquark distributions are positive at large x and become negative at small x. The denominator of Eq. (5) could vanish at some x_F points, so that the ratio is infinite at these points. Therefore, the intermediate-x_F region is especially useful for finding the detailed x dependence of the antiquark distributions.

As we have found in these analyses, the pd Drell-Yan is important for finding not only new structure functions [12, 13] but also the details of polarized antiquark distributions. At this stage, there is no experimental proposal for the polarized deuteron Drell-Yan. However, there are possibilities at FNAL, HERA, and RHIC, and we do hope that the feasibility is studied seriously at these facilities.

4 Conclusions

We have studied the polarized Drell-Yan cross-section ratio $R_{pd} = \Delta_{(T)}\sigma_{pd}/2\,\Delta_{(T)}\sigma_{pp}$. Using the recent formalism for the polarized pd processes and typical parametrizations, we have shown that it is possible to extract the information on the light antiquark flavor asymmetry ($\Delta_{(T)}\bar{u}/\Delta_{(T)}\bar{d}$). The large-$x_F$ region is very sensitive to the flavor asymmetry. Our proposal is particularly important for the transversity distributions because the $\Delta_T\bar{u}/\Delta_T\bar{d}$ asymmetry cannot be found in the W production processes. Furthermore, the intermediate-x_F region is valuable for finding the detailed x dependence of the polarized antiquark distributions.

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Figures

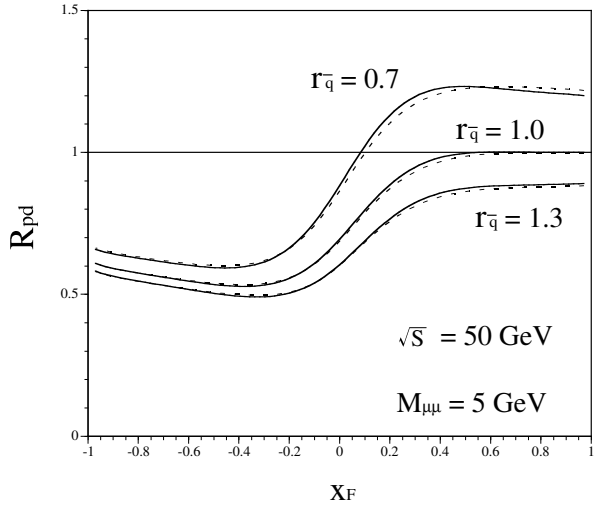

Figure 1: The Drell-Yan cross section ratio $R_{pd} \equiv \Delta_{(T)}\sigma_{pd}/2\Delta_{(T)}\sigma_{pp}$ is calculated in the leading order (LO) of α_s at $\sqrt{s} = 50$ GeV and $M_{\mu\mu} = 5$ GeV. The solid (dashed) curves indicate the longitudinally (transversely) polarized ratios. The flavor-asymmetry ratio is taken as $r_{\bar{q}} \equiv \Delta_{(T)}\bar{u}/\Delta_{(T)}\bar{d}$=0.7, 1.0, or 1.3 at Q^2=1 GeV^2. The LSS99 distributions are used for the polarized parton distributions.

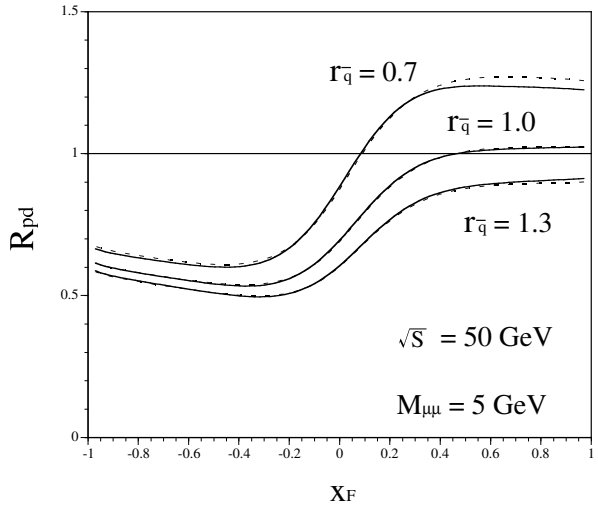

Figure 2: Next-to-leading-order (NLO) evolution results are shown. The notations are the same as those in Fig. 1.

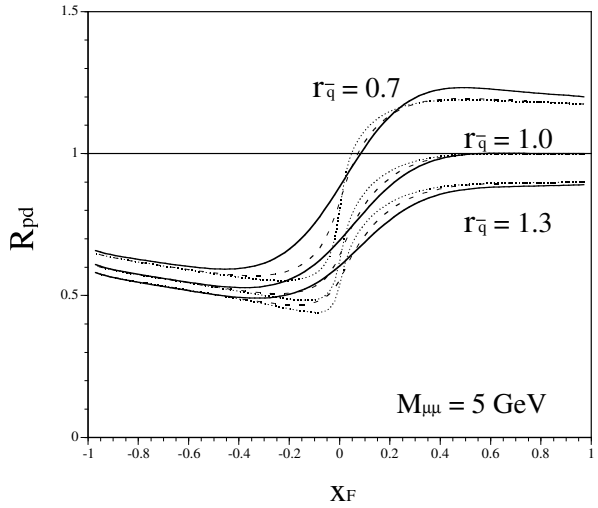

Figure 3: The dependence on the c.m. energy is shown in the LO. The input distributions are those of the LSS99. The solid, dashed, and dotted curves are the longitudinal ratios at $\sqrt{s}$ =50, 200, and 500 GeV, respectively.

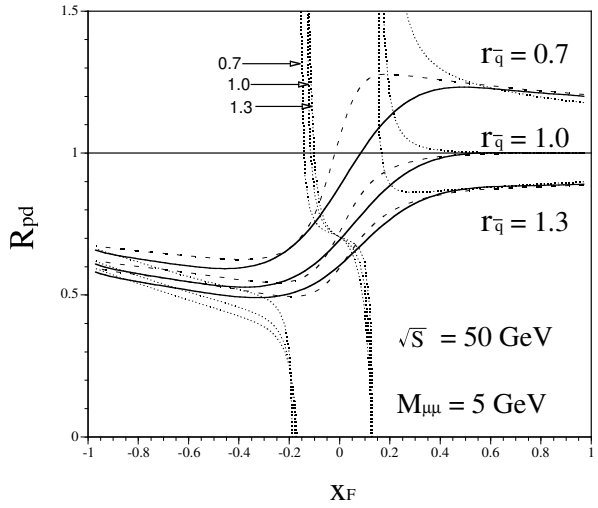

Figure 4: The dependence on the parametrization is shown in the LO case. The solid, dashed, and dotted curves are the longitudinal ratios with the LSS99, GRSV96, and GS-A parametrizations, respectively.