Drell-Yan proton-deuteron asymmetry and polarized light-antiquark distributions

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We discuss the Drell-Yan proton-deuteron (p-d) asymmetry R_{pd}, which is defined by the proton-proton and proton-deuteron cross-section ratio $\boldsymbol{\Delta}_{(T)}\boldsymbol{\sigma}^{pd}/2\boldsymbol{\Delta}_{(T)}\boldsymbol{\sigma}^{pp}$, and its relation to the polarized light-antiquark flavor asymmetry. Using a formalism of the polarized pd Drell-Yan process, we show that the R_{pd} especially in the large-x_F region is very useful for finding the flavor asymmetry in the longitudinally-polarized and transversity distributions. Our results are particularly important to study the flavor asymmetry in the transversity distributions because they cannot be measured by inclusive deep inelastic scattering and W-production process.

1. Introduction

Nowadays, flavor asymmetry of light-antiquark distributions is an established fact in unpolarized distributions.[1] At first, the unpolarized $\bar{u}/\bar{d}$ asymmetry was suggested by the NMC finding of the Gottfried-sum-rule violation. Then, NA51 and E866 collaborations investigated the $\bar{u}/\bar{d}$ ratio by measuring Drell-Yan proton-deuteron asymmetry. Their results clearly showed that the $\bar{u}$ and $\bar{d}$ distributions are different from each other. In particular, E866 data revealed detailed x dependence of the $\bar{d}/\bar{u}$ ratio. Furthermore, semi-inclusive deep inelastic scattering data which were measured by HERMES also showed the flavor asymmetry.

On the other hand, the flavor asymmetry in polarized distributions is totally unknown at this stage although there are some model predictions. Our research purpose is to study the flavor asymmetry in more detail. At this stage, the longitudinally-polarized parton distributions are mainly investigated by measuring the spin structure function g_1. However, g_1 data are not enough to find the flavor asymmetry. It may be possible to get the information about the flavor asymmetry from semi-inclusive deep inelastic scattering data[2] which were measured by SMC and HERMES. However, the precision of the present data is not enough to determine whether there exists the flavor asymmetry although the results show the tendency that the $\Delta\bar{u} - \Delta\bar{d}$ becomes positive. Situation is more serious for another polarized distributions, namely transversity distributions, since they cannot be measured by inclusive deep inelastic scattering and W-production processes because of the chiral-odd property. The W production is expected to provide important information about the flavor asymmetry in the unpolarized and longitudinally-polarized distributions. In the light of the present situation, we should study other independent processes to get the detailed information on the flavor asymmetry and to determine the major mechanism for creating the asymmetry. In this study, we investigate the method in which we use the polarized proton-deuteron (pd) Drell-Yan process with pp Drell-Yan.[3]

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In section 2, model studies are explained on the light-antiquark flavor asymmetry in longitudinally-polarized and transversity distributions $\Delta_{(T)}\bar{u} - \Delta_{(T)}\bar{d}$. Here, $\Delta_{(T)}$ denotes Δ or Δ_T for the longitudinally-polarized or transversity distribution, respectively. Then, we discuss the relation between the polarized Drell-Yan proton-deuteron (p-d) asymmetry which is defined by the ratio of the polarized pd Drell-Yan cross section to the proton-proton (pp) one $\Delta_{(T)}\sigma_{pd}/2\Delta_{(T)}\sigma_{pp}$ and the polarized flavor asymmetry in section 3. Furthermore, we show the numerical results for the flavor asymmetry effects on the Drell-Yan p-d asymmetry in section 4. Conclusions are given in section 5.

2. Theoretical predictions on the polarized flavor asymmetry

In this section, we briefly introduce the present status of the model studies on the flavor asymmetry $\Delta_{(T)}\bar{u} - \Delta_{(T)}\bar{d}$. First, as one of the origins of the flavor asymmetry, there is a perturbative-QCD contribution. Next-to-leading-order (NLO) Q^2 evolution gives rise to the difference between the $\bar{u}$ and $\bar{d}$ distributions even if the flavor-symmetric distributions are used at initial Q^2. However, its effect is not so large as to reproduce the measured asymmetry in the unpolarized distributions if the Q^2 evolution is calculated in the perturbative Q^2 range. Therefore, we expect that dominant effects come from non-perturbative mechanisms.

We have been studying the flavor asymmetry in the polarized distributions by using typical models for the unpolarized $\bar{u}/\bar{d}$ asymmetry, and we have been also investigating its effect on the Drell-Yan spin asymmetry A_{TT}.[4] One of the typical models is a meson-cloud model. In this model, we calculate the meson-nucleon-baryon (MNB) process in which the initial nucleon splits into a virtual meson and a baryon, then the virtual photon from lepton interacts with this meson. Since the lightest vector meson is ρ meson, we investigate a ρ-meson contribution to the polarized flavor asymmetry. We take into account Δ, in addition to the proton, as a final state baryon, and all the possible ρNB processes are considered. Among them, the dominant contribution comes from the process with ρ^+ meson. Because the ρ^+ has a valence $\bar{d}$ quark, this mechanism contributes to the $\bar{d}$ excess over $\bar{u}$. Note that the ρ-meson contributions to the flavor asymmetry

are also studied in Ref. 5.

Another typical model in the unpolarized case is Pauli-exclusion-principle model. Although this mechanism does not seem to explain the whole $\bar{u}/\bar{d}$ asymmetry, it is still worth while discussing the polarized asymmetry. This model for the polarized case has already studied in Ref. 6. According to the SU(6) quark model, each quark-state probabilities in the spin-up proton are given by $u^{\uparrow} = 5/3$, $u^{\downarrow} = 1/3$, $d^{\uparrow} = 1/3$, and $d^{\downarrow} = 2/3$, respectively. Since the probability of $u^{\uparrow}$ ($d^{\downarrow}$) is much larger than that of $u^{\downarrow}$ ($d^{\uparrow}$), it is more difficult to create $u^{\uparrow}$ ($d^{\downarrow}$) sea than $u^{\downarrow}$ ($d^{\uparrow}$) sea because of the Pauli-exclusion principle. Then, if we assume that the magnitude of the exclusion effect is the same as the one in the unpolarized case, $(u_s^{\downarrow} - u_s^{\uparrow})/(u_v^{\uparrow} - u_v^{\downarrow}) = (d_s - u_s)/(u_v - d_v)$ and a similar equation for $d_s^{\uparrow} - d_s^{\downarrow}$, the magnitude of $\Delta\bar{u}$ and $\Delta\bar{d}$ become -0.13 and $+0.05$, respectively. In this way, we find the $\Delta\bar{u}/\Delta\bar{d}$ flavor asymmetry from this mechanism.

We numerically calculate the flavor-asymmetric distribution $\Delta_{(T)}\bar{u} - \Delta_{(T)}\bar{d}$ by using the above model results and actual initial distributions. As a result, we find that both model predictions have similar tendency that the $\Delta_{(T)}\bar{u} - \Delta_{(T)}\bar{d}$ becomes negative. Furthermore, the meson contribution seems to be smaller than that of the exclusion model. In addition to these mechanisms, there are also some model studies on the polarized flavor asymmetry.[7)] To distinguish these mechanisms, we need detailed experimental information on the $\Delta_{(T)}\bar{u}$ and $\Delta_{(T)}\bar{d}$ asymmetry. This is the reason for investigating the possibility of finding the flavor asymmetry by the polarized *pd* Drell-Yan data.

3. Polarized proton-deuteron Drell-Yan process and flavor asymmetry

Recently, a formalism of the polarized *pd* Drell-Yan process was completed in Refs. 8 and 9. They showed that there are additional spin asymmetries compared with a spin-1/2 hadron reaction. These new spin asymmetries are related to new spin structure in a spin-1 hadron and one of major purposes to investigate the polarized *pd* Drell-Yan process is to study this new spin structure.

Here, we briefly comment on this topic although it is not the major purpose in this work. The spin structure of the spin-1/2 hadron is relatively well investigated by measuring the structure function g_1. On the other hand, there is no experimental study for the spin structure of the spin-1 hadron. In fact, we know that the new spin structure, namely, the polarized tensor distributions can be investigated by measuring the tensor structure function b_1 in the deep inelastic scattering with unpolarized lepton off the polarized deuteron. The b_1 has not be measured at this stage, but it is expected to be measured at HERMES in future. In the *pd* Drell-Yan, on the other hand, parton-model analysis suggests that only three spin asymmetries A_{LL}, A_{TT}, and A_{UQ_0} remain finite and other asymmetries vanish in the leading-twist level. In these asymmetries, the A_{UQ_0} is a new one in the spin-1 hadron. In the parton model, this spin asymmetry is expressed by

$$A_{UQ_0} = \frac{\sum_a e_a^2 \left[q_a(x_1)\, \delta\bar{q}_a^d(x_2) + \bar{q}_a(x_1)\, \delta q_a^d(x_2) \right]}{\sum_a e_a^2 \left[q_a(x_1)\, \bar{q}_a^d(x_2) + \bar{q}_a(x_1)\, q_a^d(x_2) \right]} , \qquad (1)$$

where, δq_a^d and $\delta\bar{q}_a^d$ represent the quark and antiquark tensor distributions in the deuteron. The subscript a represents quark flavor, and e_a is the corresponding quark charge. Therefore, we can study the tensor distributions also by measuring this spin asymmetry. In particular, A_{UQ_0} has an advantage to investigate the antiquark tensor distributions in comparison with the deep inelastic scattering. This topic is very interesting but we do not discuss in this paper. The details are discussed in Refs. 8 and 9, so that the interested reader may read these papers.

For investigating the flavor asymmetry, we use the results for the spin asymmetries A_{LL} and A_{TT}. Because of the existence of the tensor distribution, it was not clear whether the polarized *pd* Drell-Yan cross sections are expressed by the same forms as the *pp* ones. References 8 and 9 revealed this point. From their analysis, the difference between the longitudinally-polarized *pd* Drell-Yan cross sections is given by

$$\begin{aligned} \Delta\sigma_{pd} &= \sigma(\uparrow_L, -1_L) - \sigma(\uparrow_L, +1_L) \\ &\propto \sum_a e_a^2 \left[\Delta q_a(x_1) \Delta\bar{q}_a^d(x_2) + \Delta\bar{q}_a(x_1) \Delta q_a^d(x_2) \right], \end{aligned} \qquad (2)$$

where the $\uparrow_L$, $+1_L$, and -1_L represent the longitudinal polarization and $\sigma(pol_p, pol_d)$ represents the cross section with the proton and deuteron polarizations, pol_p and pol_d. The Δq_a^d and $\Delta\bar{q}_a^d$ are the longitudinally-polarized quark and antiquark distributions in the deuteron. The momentum fractions are given by $x_1 = \sqrt{\tau} e^{+y}$ and $x_2 = \sqrt{\tau} e^{-y}$ in the case of small P_T. Here, the τ is defined by $\tau = M_{\mu\mu}^2/s$ with dimuon mass $M_{\mu\mu}$ and the dimuon rapidity is given by $y = (1/2)\ln[(E^{\mu\mu} + P_L^{\mu\mu})/(E^{\mu\mu} - P_L^{\mu\mu})]$. In the same way, the transversely-polarized cross-section difference is given by

$$\begin{aligned} \Delta_T\sigma_{pd} &= \sigma(\phi_p = 0, \phi_d = 0) - \sigma(\phi_p = 0, \phi_d = \pi) \\ &\propto \sum_a e_a^2 \left[\Delta_T q_a(x_1) \Delta_T\bar{q}_a^d(x_2) + \Delta_T\bar{q}_a(x_1) \Delta_T q_a^d(x_2) \right], \end{aligned} \qquad (3)$$

where the ϕ is the azimuthal angle of a polarization vector. The $\Delta_T q$ and $\Delta_T\bar{q}$ are quark and antiquark transversity distributions.

The *pp* Drell-Yan cross sections are given simply by replacing the distributions in the deuteron in Eqs. (2) and (3) by the ones in the proton. We use these equations for investigating the flavor asymmetry in the polarized distributions. To study the flavor asymmetry, we define the Drell-Yan proton-deuteron (*p*-*d*) asymmetry R_{pd} by

$$\begin{aligned} R_{pd} &\equiv \frac{\Delta_{(T)}\sigma_{pd}}{2\,\Delta_{(T)}\sigma_{pp}} \\ &= \frac{\sum_a e_a^2 \left[\Delta_{(T)} q_a(x_1) \Delta_{(T)} \bar{q}_a^d(x_2) + \Delta_{(T)} \bar{q}_a(x_1) \Delta_{(T)} q_a^d(x_2) \right]}{2 \sum_a e_a^2 \left[\Delta_{(T)} q_a(x_1) \Delta_{(T)} \bar{q}_a(x_2) + \Delta_{(T)} \bar{q}_a(x_1) \Delta_{(T)} q_a(x_2) \right]}. \end{aligned} \qquad (4)$$

First, we show the behavior of R_{pd} in the large x_F ($= x_1 - x_2$) limit. Because sea-quark distributions in the proton become smaller than other distributions in this limit, the proton sea-quark terms in the numerator and denominator of Eq. (4) can be ignored. In our analysis, we neglect the nuclear effects in the deuteron and assume the isospin symmetry. Then, the distributions in the deuteron can be written in terms of the

distributions in the proton as

$$\begin{aligned}
&\Delta_{(T)}u^d = \Delta_{(T)}u + \Delta_{(T)}d, \quad && \Delta_{(T)}d^d = \Delta_{(T)}d + \Delta_{(T)}u,\\
&\Delta_{(T)}s^d = 2\Delta_{(T)}s, && \Delta_{(T)}\bar{u}^{\,d} = \Delta_{(T)}\bar{u} + \Delta_{(T)}\bar{d},\\
&\Delta_{(T)}\bar{d}^{\,d} = \Delta_{(T)}\bar{d} + \Delta_{(T)}\bar{u}, && \Delta_{(T)}\bar{s}^{\,d} = 2\Delta_{(T)}\bar{s}.
\end{aligned} \tag{5}$$

However, for a precise comparison with future experimental data, the nuclear corrections should be properly included. Using these relations, R_{pd} becomes

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

where $x_1 \to 1$ and $x_2 \to 0$. Because of the $\Delta_{(T)}\bar{u} - \Delta_{(T)}\bar{d}$ factor, the ratio R_{pd} simply becomes one if the distribution $\Delta_{(T)}\bar{u}$ is equal to $\Delta_{(T)}\bar{d}$. If we assume that the valence-quark distributions satisfy $\Delta_{(T)}u_v(x \to 1) \gg \Delta_{(T)}d_v(x \to 1)$, Eq. (6) can be written in a more simple form as

$$\begin{aligned}
R_{pd}(x_F \to 1) &= 1 - \left[\frac{\Delta_{(T)}\bar{u}(x_2) - \Delta_{(T)}\bar{d}(x_2)}{2\,\Delta_{(T)}\bar{u}(x_2)} \right]_{x_2 \to 0}\\
&= \frac{1}{2} \left[1 + \frac{\Delta_{(T)}\bar{d}(x_2)}{\Delta_{(T)}\bar{u}(x_2)} \right]_{x_2 \to 0}.
\end{aligned} \tag{7}$$

From this equation, it is clear that R_{pd} becomes larger (smaller) than one if the $\Delta_{(T)}\bar{u}$ distribution is negative as suggested by recent parametrizations and if the $\Delta_{(T)}\bar{u}$ distribution is larger (smaller) than the $\Delta_{(T)}\bar{d}$.

Next, we discuss the behavior of R_{pd} in another limit, namely $x_F \to -1$. In this limit, the ratio R_{pd} becomes

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

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

$$R_{pd}(x_F \to -1) = \frac{1}{2} \left[1 + \frac{\Delta_{(T)}\bar{d}(x_1)}{4\,\Delta_{(T)}\bar{u}(x_1)} \right]_{x_1 \to 0}. \tag{9}$$

In this equation, we find the extra factor 4 in comparison with the equation for $x_F \to 1$ limit. Therefore, R_{pd} in this limit is not as sensitive to the $\Delta_{(T)}\bar{u}/\Delta_{(T)}\bar{d}$ asymmetry as the one in the large-x_F limit although we can investigate the flavor asymmetry also in this limit. From Eq. (9), if the $\Delta_{(T)}\bar{u}$ distribution is equal to the $\Delta_{(T)}\bar{d}$, R_{pd} becomes $5/8 = 0.625$ and if the $\Delta_{(T)}\bar{u}$ distribution is larger (smaller) than the $\Delta_{(T)}\bar{d}$, the ratio becomes larger (smaller) than this value.

From these analyses, we find that we can investigate the flavor asymmetry by measuring the polarized *pd* Drell-Yan process and taking the *pd* and *pp* cross-section ratio. In particular, R_{pd} in the large-x_F and small-x_F regions are useful to find a signature for the flavor asymmetry.

4. Numerical results

We numerically calculate the Drell-Yan p-d asymmetry R_{pd} by using a recent parametrization. In this section, we show the numerical results and discuss the flavor asymmetry effect on the R_{pd}.[3] As initial distributions, we use the 1999 version of the LSS (Leader-Sidorov-Stamenov) parametrization[10] for the longitudinally-polarized distributions. The LSS99 distributions are given at $Q^2 = 1\,\mathrm{GeV}^2$ by assuming SU(3) flavor-symmetric sea. For the transversity distributions, we simply assume that they are the same as the longitudinal distributions at $Q^2 = 1\,\mathrm{GeV}^2$ by considering the quark-model predictions. Furthermore, we take center-of-mass energy $\sqrt{s} = 50\,\mathrm{GeV}$ and dimuon mass $M_{\mu\mu} = 5\,\mathrm{GeV}$. Although there are some model predictions for the flavor asymmetry in the polarized distributions as explained in section 2, we simply take the $\Delta_{(T)}\bar{u}/\Delta_{(T)}\bar{d}$ ratio as

$$r_{\bar{q}} \equiv \frac{\Delta_{(T)}\bar{u}}{\Delta_{(T)}\bar{d}} = 0.7,\ 1.0,\ \text{or}\ 1.3, \tag{10}$$

at $Q^2 = 1\,\mathrm{GeV}^2$ in the following analysis. The initial distributions with these $r_{\bar{q}}$ are evolved to those at $Q^2 = M_{\mu\mu}^2$ by leading-order (LO) evolution equations. We use the FORTRAN programs which are provided in Ref. 11 for calculating the Q^2 evolution of the longitudinally-polarized and transversity distributions. Then, the *pd*/*pp* Drell-Yan cross-section ratio R_{pd} is calculated for each $r_{\bar{q}}$. The results are shown in Fig. 1. The solid and dashed curves represent the longitudinal and transverse results, respectively. As clearly shown by this figure, the flavor-symmetric ($r_{\bar{q}} = 1.0$) results become one in the large-x_F limit and 0.625 in the small-x_F limit as discussed in the previous section. The results with the flavor asymmetry deviate from the flavor-symmetric ones. In particular, the deviations are conspicuous in the large-x_F region. From these results, we find that the R_{pd} in the large-x_F region is very useful for finding the flavor asymmetry in the polarized distributions. Furthermore, we also find that there is almost no difference between the longitudinal and transverse results in this kinematical range if the initial distributions are identical.

In Fig. 2, we show NLO evolution results. We evolve the same LSS99 distributions at $Q^2 = 1\,\mathrm{GeV}^2$ to those at $Q^2 = M_{\mu\mu}^2$ by

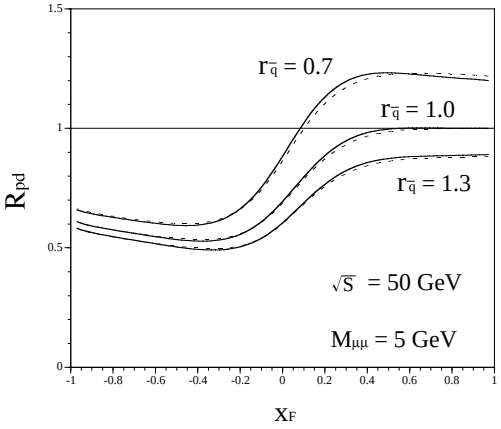

Fig. 1. LO evolution results for the R_{pd}. The solid (dashed) curves indicate the longitudinally (transversely) polarized ratios (from Ref. 3).

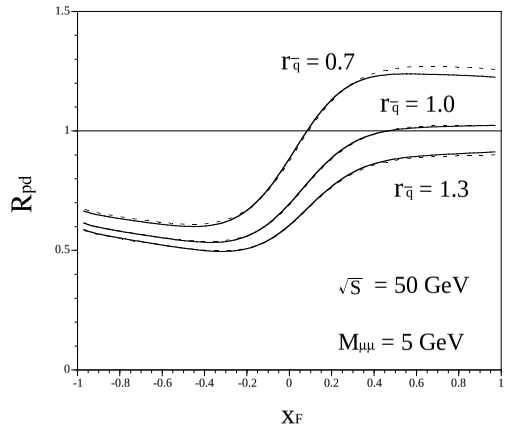

Fig. 2. NLO evolution results for the R_{pd}. The notations are the same as those in Fig. 1 (from Ref. 3).

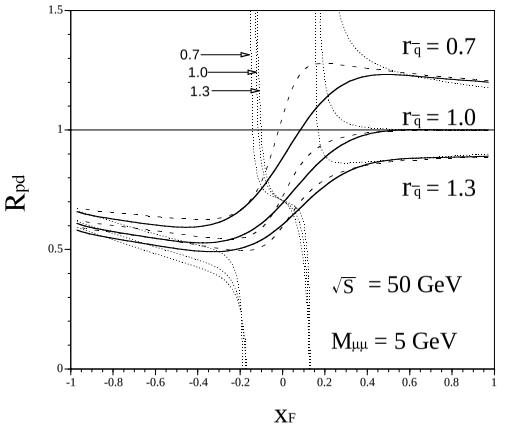

Fig. 4. The parametrization dependence. The solid, dashed, and dotted curves are the longitudinal ratios with the LSS99, GRSV96, and GS-A, respectively (from Ref. 3).

NLO evolution equations. The results are almost the same as the LO ones. However, there is slight deviation. For example, the ratio R_{pd} in the large-x_F region is slightly different from one although antiquark distributions are flavor symmetric at $Q^2 = 1\,\mathrm{GeV}^2$. It is because the NLO evolution gives rise to the flavor asymmetry. Although such perturbative-QCD effect is not so large in this kinematical region as clearly shown by this figure, we should include the NLO contributions for a precise analysis.

Next, we discuss the dependence on the center-of-mass energy $\sqrt{s}$. The results for the longitudinal ratio at the RHIC energies $\sqrt{s} = 200$ and 500 GeV are shown in Fig. 3. The solid, dashed, and dotted curves indicate the results at $\sqrt{s} = 50$, 200, and 500 GeV, respectively. The calculated results are almost the same as those at $\sqrt{s} = 50$ GeV in the large- and small-x_F regions. However, the ratio in the intermediate-x_F region has much dependence on the c.m. energy and becomes a steeper function of x_F as $\sqrt{s}$ increases. From these results, we find that the R_{pd} in the intermediate-x_F region is sensitive to the details of the distributions.

Finally, we show the dependence on the used parametrizations. In our analysis, we use the LSS99 distributions. In order to show the parametrization dependence, we employ the GRSV96[12] and the Gehrmann-Stirling set A (GS-A)[13] distributions. The ratios R_{pd} calculated with these initial distributions are shown in Fig. 4. The solid, dashed, and dotted curves represent the results with LSS99, GRSV96, and GS-A parametrizations. As shown in this figure, there is not so much difference between the LSS99 and GRSV results. However, the GS-A results has very different behavior especially in the intermediate-x_F region. Because the GS-A antiquark distribution is positive in the large-x region but becomes negative in the small-x region, while the LSS99 and GRSV ones are negative in the whole x, the denominator of the R_{pd} becomes zero at certain x and the ratio goes to infinity at such x points. Therefore, the R_{pd} in the intermediate-x_F region is especially useful for determining the detailed x dependence of the polarized antiquark distributions.

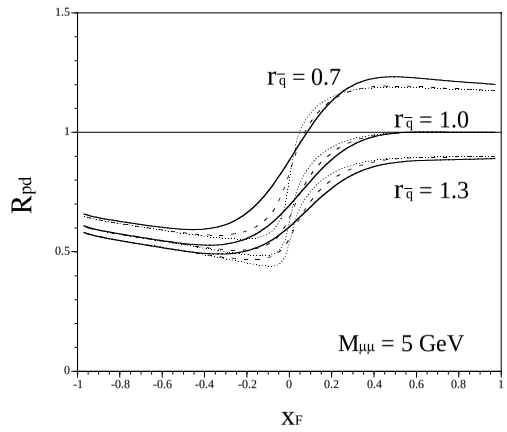

Fig. 3. The c.m. energy dependence. The solid, dashed, and dotted curves are the longitudinal ratios at $\sqrt{s} = 50$, 200, and 500 GeV, respectively (from Ref. 3).

From these numerical analyses, we find that the R_{pd} is very valuable for investigating the details of the antiquark distributions. At this stage, there is no proposal for the polarized pd Drell-Yan experiment. However, we think that there are possibilities at FNAL, HERA, and RHIC.

5. Conclusions

We have studied the Drell-Yan proton-deuteron asymmetry R_{pd} which is defined by pd and pp cross-section ratio $\Delta_{(T)}\sigma_{pd}/2\,\Delta_{(T)}\sigma_{pp}$. Using the formalism for the polarized pd Drell-Yan process, we have shown that the R_{pd} is very useful for finding the light-antiquark flavor asymmetry in the polarized distributions ($\Delta_{(T)}\bar{u}/\Delta_{(T)}\bar{d}$), especially in the large-x_F region. We have also shown the dependence on the center-of-mass energy and the used parametrizations. As a result, we have found that the R_{pd} in the intermediate-x_F region is valuable for determining the detailed x dependence of the polarized antiquark distributions. Our results are important particularly for the transversity distributions for which W production does not provide information on the $\Delta_T\bar{u}/\Delta_T\bar{d}$ asymmetry because of their chiral-odd nature.

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