Probing Polarized Gluon Distributions through Charmed Hadron Production in Polarized pp Collisions at BNL–RHIC Energy

TOSHIYUKI MORII
Faculty of Human Development,
Kobe University,
Nada, Kobe 657-8501, JAPAN
Electronic address: morii@kobe-u.ac.jp

KAZUMASA OHKUMA
Department of Information Science,
Fukui University of Technology,
Gakuen, Fukui, 910-8505, JAPAN
Electronic address: ohkuma@fukui-ut.ac.jp

ABSTRACT

In order to extract information about behavior of polarized gluons in the nucleon, charmed hadron productions, i.e. $D^*$ meson and $\Lambda^+_c$ baryon productions, are studied in polarized $pp$ reactions at BNL-RHIC energy. For these processes, the spin correlation asymmetry $D_{LL}$ between the target proton and the produced charmed hadron, and its statistical sensitivity $\delta D_{LL}$ are calculated. From analyses on these processes, we found that the pseudo-rapidity distribution of $D_{LL}$ in the limited transverse momentum region is quite effective for distinguishing the model of polarized gluons as well as the model of spin-dependent fragmentation functions.

PACS number(s): 13.85.Ni, 13.88.+e, 14.20.Lq, 14.40.Lb,

Keywords: Proton Spin Structure, Polarized Gluon Distribution, Polarized pp Reaction, Charmed Hadron Production.
1. Introduction

Though the proton is one of the most familiar nucleons, the origin of its spin is still an open question. About 15 years ago, the European Muon Collaboration (EMC) reported surprising data on the polarized structure function of proton $g_1^p(x, Q^2)$ [1], indicating that the spin of the proton cannot be described by the naive quark model. Disagreement of the result extracted from the EMC data with theoretical predictions has been called the “Proton Spin Puzzle”, which is not yet solved well in spite of many follow-up experiments and a great development of theoretical analyses. It is still one of the challenging themes in nuclear and particle physics [2]. According to the parton-model concept inspired by quantum chromodynamics (QCD), the proton spin satisfies the following sum rule;

$$\frac{1}{2} = \int_0^1 dx \left[ \frac{1}{2} \sum_q (\Delta q(x) + \Delta \bar{q}(x)) + \Delta g(x) \right] + < L >_{q+g}$$

where $\frac{1}{2}$ on the left-hand side is a spin of proton, while $\Delta q(x), \Delta \bar{q}(x)$ and $\Delta g(x)$ are the spin carried by quarks, anti-quarks and gluons, respectively. In the right-hand side of Eq.(1), integration is performed over all Bjorken-$x$ region. $< L >_{q+g}$ represents the orbital angular momentum of quarks and gluons in the proton. An important thing is to know how large each of these component is and then to understand, based on QCD, what the underlying dynamics of this sum rule is. These days the behavior of valence quarks in the proton has been considerably well understood with great efforts. However, the knowledge of gluons in the proton is still poor. Therefore, to solve the proton spin puzzle, it is very important to obtain a good information about gluon polarization in the proton. So far, the gluon distribution in the proton has been studied mainly through deep inelastic scattering (DIS) of polarized leptons (electrons and muons) off polarized nucleons. However, now we are in a new stage; the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) which gives us another unique place for probing the proton structure via polarized proton–polarized proton scattering has started to work. For the RHIC experiment, the following processes are already proposed to study the behavior of polarized gluons in the proton [3];

- High-$p_T$ (“prompt”) photon production, $\bar{p}p \rightarrow \gamma X$,
- Jet production, $\bar{p}p \rightarrow jet(s)X$,
• Heavy-flavor production, $\vec{p}\vec{p} \rightarrow c\bar{c}X, b\bar{b}X$,

where the particle with an arrow means that it is polarized.

In addition to these processes, we propose other interesting processes, i.e. the polarized charmed hadron productions in the polarized proton–unpolarized proton collision:

$$p\vec{p} \rightarrow c\bar{c} \rightarrow \bar{D}^{++}X,$$

$$p\vec{p} \rightarrow c\bar{c} \rightarrow \bar{\Lambda}_c^+X,$$

by expecting that they also could be observed in the forthcoming RHIC experiment. In the lowest order of QCD, a charm quark being one of the constituents of charmed hadrons is produced via gluon–gluon fusion ($gg \rightarrow c\bar{c}$) and quark–anti-quark annihilation ($q\bar{q} \rightarrow c\bar{c}$) processes in proton–proton collisions (Fig.1). Then, if we could separate kinematically a contribution of $gg \rightarrow c\bar{c}$ from $q\bar{q} \rightarrow c\bar{c}$ and pick up $gg \rightarrow c\bar{c}$ clearly, we could extract a good information about gluon polarization by observing the spin correlation asymmetries between the initial proton and these produced charmed hadrons, since the cross section of gluon fusion is directly proportional to the gluon distribution.

Concerning the $\Lambda_c^+$ production, in a couple of years ago we analyzed the spin correlation between the initial proton and produced $\Lambda_c^+$ in the diffractive regions of the process $p\vec{p} \rightarrow p\bar{\Lambda}_c^+X$, where Pomeron interactions play an important role [4] and pointed out that the process is promising for extracting the polarized gluon distribution. In this paper, we develop those analyses to another important kinematical region, i.e. the central region of collision. The present analysis is complementary to those previous analyses and should give us additional information on the polarized gluon distribution in the different kinematical region \(^{\sharp 1}\).

This paper is organized as follows. In the next section, we explain why we focus on charmed hadron production in this work. Then, we introduce spin correlation observable and present a theoretical formulation of our calculation in Sec. 3. In section 4, we show the result of our numerical calculation. Finally, Sec. 5 is devoted to conclusion, including discussion and summary.

\(^{\sharp 1}\)The preliminary analysis of the $\Lambda_c^+$ production was done in ref [5].
Figure 1: Diagrams for $p\bar{p} \rightarrow \bar{h}_c^+ X$ at the lowest order (left) and its subprocesses (right), where $\bar{h}_c^+$ means a polarized charmed hadron with positive charge. Dashed-lines in the left figure stand for partons which are emitted from initial protons.

2. Polarized charmed hadron production in $pp$ collisions

As described above, we will focus on two processes of charmed hadron production; one is polarized $D^{*+}$ meson production and another is polarized $\Lambda_c^+$ production. Then, what is so special about these processes? and why are they so interesting? This is because in these processes, we can regard the spin of the produced charmed hadron to be same as the one of the charm quark as described below;

- **$D^{*+}$ meson**
  Since the $D^{*+}$ meson is in the $^3S_1$ state in the non-relativistic quark model, the spin of $D^{*+}$ meson is carried by a charm quark and an anti-down quark whose spins are combined in parallel. Therefore, the spin direction of the $D^{*+}$ meson and the spin direction of the constituent charm quark are expected to be same.

- **$\Lambda_c^+$ baryon**
  The $\Lambda_c^+$ is composed of a heavy charm quark and antisymmetrically combined light up and down quarks. Hence, the $\Lambda_c^+$ spin is basically carried by a charm quark.

Furthermore, it is expected to be very rare for a produced charm quark to change its spin direction during its decay into a charmed hadron, since the charm quark is significantly heavy and the spin flip interaction being proportional to $1/m_c$ ($m_c$ is charm quark mass) is small. Therefore, if these processes are originated from
gluon fusion, spin-dependent observables for produced charmed hadrons directly
depend on the polarization of gluons in the initial proton and thus, observation of
the polarization of the produced charmed hadron could give us a good information
about polarized gluons in the proton.

Concerning the above discussion, it is worth while to comment on contribu-
tion of light-quark fragmentation to charmed hadron production. In the case of
charmed hadron production by light-quark fragmentation, a light-quark produced
in a hard parton subprocess must pick up a charm quark created from vacuum to
make a charmed hadron. However, the probability of charm-quark pair creation
is extremely small, estimated to be $10^{-11}$ compared to the one for $u\bar{u}$ and $d\bar{d}$ pair
creation [6]. Therefore, in charmed hadron production we can safely neglect the
contribution of light-quark fragmentation. This is rather different from the case of
$\Lambda$ production [7], where the probability of $s\bar{s}$ pair creation from vacuum cannot be
neglected.

3. Spin correlation observables and cross sections

To study the polarized gluon distribution in the proton, we introduce the spin cor-
relation asymmetry between the polarized target-proton and the produced charmed
hadron defined by;

$$D_{LL} = \frac{d\sigma_{++} - d\sigma_{+-} + d\sigma_{-+} - d\sigma_{--}}{d\sigma_{++} + d\sigma_{+-} + d\sigma_{-+} + d\sigma_{--}}$$

$$\equiv \frac{d\Delta\sigma/dX}{d\sigma/dX}, \ (X = p_T \ or \ \eta),$$

where $d\sigma_{+-}$, for example, denotes the spin-dependent differential cross section with
the positive helicity of the target proton and the negative helicity of the produced
charmed hadron. $p_T$ and $\eta$, which are represented by $X$ in Eq.(4), are transverse
momentum and pseudo-rapidity of the produced charmed hadron, respectively.

In order to perform our analyses, we take the proton–proton center of mass
system(CMS). In this system, four momentum $p_i$ of each particle $i$ is defined as
follows;

\[ p_{A/B} = \frac{\sqrt{s}}{2} (1, \mp \beta, 0), \quad \beta \equiv \sqrt{1 - \frac{4m_i^2}{s}} \]

\[ p_{h_c} = (E_{h_c}, p_L, p_T) \]

\[ = (\sqrt{m_{h_c}^2 + p_T^2\cosh^2 \eta}, p_T \sinh \eta, p_T), \]

\[ p_{a/b} = x_{a/b} p_{A/B}, \quad p_c = \frac{p_{h_c}}{z}, \]

where the parameters in parentheses denote the energy, the longitudinal momentum and the transverse momentum, in this order. \( m_i \) stands for the mass of the particle \( i \) (\( i = p \) for proton and \( i = h_c \) for \( \Lambda_c^+ \) or \( D^{*+} \)). \( x_{a/b} \) and \( z \) are momentum fractions of the parton to the proton and of the charmed hadron to the charm quark, respectively. Here, notice that we define the momentum of unpolarized and polarized proton as \( p_A \) and \( p_B \), respectively. In addition, we regard the direction of \( p_B \) as the positive \( z \)-axis.

According to the quark-parton model, \( p_T \)- or \( \eta \)-dependent differential cross section, \( d\Delta\sigma/dX \), is given by, \(^{22}\)

\[
\frac{d\Delta\sigma}{dX} = \int_{Y_{\text{min}}}^{Y_{\text{max}}} \int_{x_{\text{min}}}^{x_{\text{max}}} \left[ g_{q_{a/b}}(x_a, Q^2) \Delta g_{q_{\bar{b}}/\bar{p}_B}(x_b, Q^2) \frac{d\Delta \hat{\sigma}(gg \rightarrow c\bar{c})}{dt} + \sum_{q=u,d,s,\bar{u},\bar{d},\bar{s}} \left\{ q_{a/b}(x_a, Q^2) \Delta q_{\bar{q}}/\bar{p}_B(x_b, Q^2) + \Delta q_{a/b}(x_a, Q^2) q_{\bar{q}}/\bar{p}_B(x_b, Q^2) \right\} \frac{d\Delta \hat{\sigma}(q\bar{q} \rightarrow c\bar{c})}{dt} \right] \]

\[
\times \Delta D_{h_c}^{+}/c(z) Jdxdy, \quad (X, Y = p_T \text{ or } \eta (X \neq Y))
\]

where \( g_{q_{a/b}}(x_a, Q^2) \) and \( \Delta g_{q_{\bar{b}}/\bar{p}_B}(x_b, Q^2) \) are the unpolarized and polarized gluon distribution functions, respectively, and \( q_{q_{\bar{b}}/(q_{\bar{b}})/p_{A}(\bar{p}_B)}(x_{a/b}, Q^2) \) and \( \Delta q_{q_{\bar{b}}/(q_{\bar{b}})/p_{A}(\bar{p}_B)}(x_{a/b}, Q^2) \) denote the unpolarized and polarized distributions, respectively, of the quark and anti-quark. \( \Delta D_{h_c}^{+}/c(z) \) represents the spin-dependent fragmentation function of the outgoing charm quark decaying into a polarized charmed hadron. The spin-dependent differential cross sections of the subprocess is given by \(^{23}\)

\[
\frac{d\Delta \hat{\sigma}(gg \rightarrow c\bar{c})}{dt} = \frac{\pi \alpha_s^2}{s^2} \left[ \frac{m_c^2}{24} \left\{ \frac{9\hat{t}_1 - 19\hat{u}_1}{\hat{t}_1\hat{u}_1} + \frac{8\hat{s}}{\hat{t}_1} \right\} + \frac{\hat{s}}{6} \left\{ \frac{\hat{t}_1 - \hat{u}_1}{\hat{t}_1\hat{u}_1} \right\} - \frac{3}{8} \left\{ \frac{2\hat{t}}{\hat{s}} + 1 \right\} \right],
\]

\(^{22}\)In Eq.(6), \( X \) or \( Y \) mean \( p_T \) or \( \eta \). Thus, if \( X = p_T \), then \( Y = \eta \), and vice versa.

\(^{23}\)These algebraic calculations are carried out using FORM [8].
\[
\frac{d\Delta\hat{\sigma}(q\bar{q} \rightarrow c\bar{c})}{dt} = \frac{\pi \alpha_s^4}{g} \left\{ 2m_c^2(\hat{u}_1 - \hat{t}_1) - (\hat{u}_1^2 - \hat{t}_1^2) \right\},
\]

and the Jacobian, \( J \), which transforms the variables \( z \) and \( \hat{t} \) into \( p_T \) and \( \eta \), is given by

\[
J \equiv \frac{2s\beta p_T^2 \cosh \eta}{z\hat{s}\sqrt{m_c^2 + p_T^2 \cosh^2 \eta}},
\]

where we defined the following variables:

\[
s = (p_A + p_B)^2,
\]
\[
\hat{t} = (p_B - p_{hc})^2 - m_p^2 - m_{hc}^2 = -\sqrt{s} \left[ \sqrt{m_{hc}^2 + p_T^2 \cosh^2 \eta - \beta p_T \sinh \eta} \right],
\]
\[
\hat{u} = (p_A - p_{hc})^2 - m_p^2 - m_{hc}^2 = -\sqrt{s} \left[ \sqrt{m_{hc}^2 + p_T^2 \cosh^2 \eta + \beta p_T \sinh \eta} \right].
\]

In Eq.(6), the minima of \( x_a \) and \( x_b \) are given by

\[
x_{a}^{\text{min}} = \frac{x_1}{1 - x_2}, \quad x_{b}^{\text{min}} = \frac{x_2x_1}{x_a - x_1}
\]

with

\[
x_1 \equiv -\frac{\hat{t}}{s - 2m_p^2}, \quad x_2 \equiv -\frac{\hat{u}}{s - 2m_p^2}.
\]

The unpolarized differential cross section for this process is calculated by replacing spin-dependent functions \( \Delta g(x), \Delta q(x), \Delta D(z) \) and \( \frac{d\Delta\hat{\sigma}}{dt} \) by spin-independent ones \( g(x), q(x), D(z) \) and \( \frac{d\hat{\sigma}}{dt} \), respectively \(^{24}\) and we use it to estimate the denominator of \( D_{LL} \).

4. Numerical calculation

To carry out a numerical calculation of \( D_{LL} \), we used, as input parameters, \( m_c = 1.20 \text{ GeV} \), \( m_p = 0.938 \text{ GeV} \), \( m_{D^+} = 2.01\text{GeV} \) and \( m_{\Lambda_c^+} = 2.28 \text{ GeV} \) \([10]\). In addition, we used the AAC \([11]\) and GRSV01 \([12]\) parameterization models for the polarized parton distribution function and the GRV98 \([13]\) model for the unpolarized one, and set the scaling variable \( Q^2 \) as \( Q^2 = p_T^2 \). Though both AAC

\(^{24}\)The spin-independent subprocess differential cross section \( \frac{d\hat{\sigma}}{dt} \) was given in Ref. [9]
and GRSV01 models excellently reproduce the experimental data on the polarized structure function of nucleons $g_1(x)$, the polarized gluon distributions for those models are quite different. In other words, the data on polarized structure function of nucleons $g_1(x)$ alone are not enough to distinguish the model of gluon distributions. Since the process is semi-inclusive, it is necessary to know the fragmentation function of a charm quark to $D^{*+}$ or $\Lambda_c^+$ to carry out numerical calculations. For the spin–independent fragmentation function $D_{hc/c}(z)$, we use the Peterson fragmentation function which was proposed by Peterson et al. [14] a long time ago and has been widely used for phenomenological analyses. This fragmentation function include one free parameter $\epsilon_h$ which is determined by experimental analysis. In this work, we take $\epsilon_{D^*} = 0.078$ [15] and $\epsilon_{\Lambda_c} = 0.25$ [16] for $D^{*+}$ production and $\Lambda_c^+$ production, respectively. Furthermore, for the spin-dependent fragmentation function of a charm quark decaying into polarized charmed hadrons, $\Delta D_{hc/c}(z)$, we have no information about it at present, since we have no data on polarized charmed hadron productions. Therefore, here we simply assume the spin–dependent fragmentation function to be parametrized [17] as

$$\Delta D_{hc/c}(z) = C_{hc/c} D_{hc/c}(z),$$  \hspace{1cm} (11)$$

where $C_{hc/c}$ is a scale-independent spin-transfer coefficient. We consider the following two models:

(A) $C_{hc/c} = 1$ (non-relativistic quark model)

(B) $C_{hc/c} = z$ (Jet fragmentation model [18]).

According to the consideration mentioned in sec.2, if the spin of the charmed hadron is same as the spin of the charm quark produced in the subprocess, the model (A) might be a reasonable scenario §5. Concerning the model (B), we follow the analysis for $\Lambda$ production [18] and apply it to $\Lambda_c^+/D^{*+}$ productions.

Since the charm quark is heavy, the Bjorken–$x$ of the parton taking part in charm quark pair production in the subprocess is not very large for $pp$ collisions with an appropriate energy. In this case, a charm quark is expected to be dominantly produced via gluon–gluon fusion because of the rather large gluon distribution. However, since valence quark densities become larger in large $x$ region, we could not neglect a contribution from a quark–anti-quark annihilation $q\bar{q} \rightarrow c\bar{c}$ in high

§5From HERMES experiment, even the case of $\Lambda$ baryon which include lighter $s$ quark, a fragmentation function based on the naive-quark-parton model seems to be reasonable scenario [19]. Therefore, the model (A) must not be also an unreasonable scenario for $\Lambda_c^+/D^{*+}$ productions.
Therefore, in order to get a good information on the gluon polarization, we must find the kinematical region where \( gg \rightarrow c \bar{c} \) dominates over \( q \bar{q} \rightarrow c \bar{c} \). To do so, we calculated the \( p_T \) distribution of the cross sections \( d\Delta\sigma/dp_T , d\sigma/dp_T \) and spin correlation asymmetries \( D_{LL} \) for \( D^{*+} \) and \( \Lambda^+_c \) productions at \( \sqrt{s}=200\text{GeV} \) \((\sqrt{s}=500\text{GeV})\) as shown in Fig. 2 (Fig. 3) and Fig. 4 (Fig. 5), respectively. In the left panel of these figures, we present the results only for the model (A), since the purpose of this analysis is to compare a contribution of \( gg \rightarrow c \bar{c} \) with the one of \( q \bar{q} \rightarrow c \bar{c} \). Since in the \( p_T \) region of \( 3 \leq p_T \leq 5 \text{ GeV} \), the cross section, \( d\Delta\sigma/dp_T \) and \( d\sigma/dp_T \), of \( gg \rightarrow c \bar{c} \) and \( q \bar{q} \rightarrow c \bar{c} \) do not change much from the one for \( gg \rightarrow c \bar{c} \) alone. Therefore, we can say that a contribution from the subprocess \( q \bar{q} \rightarrow c \bar{c} \) can be safely neglected in the region of \( 3 \leq p_T \leq 5 \text{ GeV} \).

We also calculated \( D_{LL} \) as a function of \( \eta \) for 3 kinematical regions of \( \eta \), i.e. (i) \(-0.5 \leq \eta \leq 0\), (ii) \(-0.5 \leq \eta \leq 0.5\), and (iii) \(0 \leq \eta \leq 0.5\). However, since the result for the region (i) distinguishes most clearly a contribution of \( q \bar{q} \rightarrow c \bar{c} \) from the one of \( gg \rightarrow c \bar{c} \), we show only the result for the region (i) in Fig. 2 \sim Fig. 5. For this limited \( p_T \) region \( (3 \leq p_T \leq 5 \text{ GeV}) \), \( D_{LL} \) for \( D^{*+} \) and \( \Lambda^+_c \) production are shown in Fig. 6 \sim Fig. 7, respectively, at \( \sqrt{s} = 200\text{GeV} \) and \( \sqrt{s}=500\text{GeV} \), where we see a rather big model-dependence of polarized gluons and also the spin-dependent fragmentation functions.

Furthermore, to know how \( D_{LL} \) is sensitive to the behavior of polarized gluons in the proton, we calculated the statistical sensitivities of \( D_{LL} \), i.e. \( \delta D_{LL} \), which is defined by the following formula [20];

\[
\delta D_{LL} \simeq \frac{1}{P|\alpha|} \sqrt{\frac{3}{\epsilon L \sigma}}. \tag{12}
\]

To numerically estimate the value of \( \delta D_{LL} \), we used the following parameters: the beam polarization; \( P = 70\% \), a integrated luminosity; \( L=320\text{pb}^{-1}(800\text{pb}^{-1}) \) for \( \sqrt{s} = 200 \text{ (500)} \text{ GeV} \) [3], the trigger efficiency; \( \epsilon = 10\% \) for detecting produced charmed hadron events, decay asymmetry parameter; \( \alpha = 1.0 \) \((0.98)\) for \( D^{*+} \) \((\Lambda^+_c) \) decay and a branching ratio; \( b_{D^{*+}} \equiv \text{Br}(D^{*+} \rightarrow D^0\pi^+)\text{Br}(D^0 \rightarrow K^-\pi^+) \simeq 2.5 \times 10^{-2} \), \( b_{\Lambda^+_c} \equiv \text{Br}(\Lambda^+_c \rightarrow \Lambda \pi^+)\text{Br}(\Lambda \rightarrow p\pi^-) \simeq 5.8 \times 10^{-3} \) [10]. \( \sigma \) denotes

---

\(^{26}\text{In order to determine the polarization of } D^{*+} \text{ and } \Lambda^+_c, \text{ observation of the angular distribution for decay channels of these particles is necessary.} \) Practically this could be done by detecting charged particles in final the state.
the unpolarized cross section integrated over a corresponding $\eta$ region. The factor 3 in Eq. (12) is an acceptance factor for our processes [20]. In Figs. 6 and 7, statistical sensitivities, $\delta D_{LL}$, are attached only to the dashed line of $D_{LL}$ which were calculated using the GRSV01 parametrization model of polarized partons and the non-relativistic fragmentation model (model (A)) $^{57}$. As shown here, statistical sensitivities $\delta D_{LL}$ are so small that the processes must be feasible for measuring the $D_{LL}$.

From these results, we see that the $\eta$ distributions of $D_{LL}$ are effective for testing the model of not only polarized gluon distributions but also spin-dependent fragmentation functions for all cases ($D^{*+}$ production and $\Lambda_c^+$ production) calculated at $\sqrt{s} = 200$ GeV and 500 GeV. Especially, $\eta$ distributions of $D_{LL}$ for $D^{*+}$ productions are quite promising, though the magnitude of $D_{LL}$ becomes smaller with increasing center of mass energy from $\sqrt{s} = 200$ GeV to 500 GeV.

![Figure 2](image_url)

Figure 2: The cross sections (left panel) and $D_{LL}$ (right panel) for $D^{*+}$ productions as a function of $p_T$ at $\sqrt{s}=200$ GeV. Here, $gg$, $q\bar{q}$ and $gg + q\bar{q}$ shown in the parenthesis at explanatory notes correspond to the subprocess taken into consideration.

## 5. Conclusion

In order to get information about polarized gluons in the proton, we proposed two charmed hadron production processes, i.e. polarized $D^{*+}$ meson productions and polarized $\Lambda_c^+$ baryon productions, which will be observed in the forthcoming RHIC experiments. As described in Introduction, the processes contain two

$^{57}$Note that as shown in Eq.(12), $\delta D_{LL}$ does not depend on both the model of polarized gluons and the model of fragmentation functions.
production mechanisms, gluon–gluon fusion ($gg \rightarrow c\bar{c}$) and quark–anti-quark annihilation ($q\bar{q} \rightarrow c\bar{c}$). Thus, to study the gluon polarization in the proton, it is necessary to find the kinematical region where $gg \rightarrow c\bar{c}$ dominates over $q\bar{q} \rightarrow c\bar{c}$.

From the numerical calculation at the lowest order of QCD, we found that the $\eta$ distribution of $D_{LL}$ in the limited $p_T$ region ($3 \leq p_T \leq 5$ GeV) is quite promising for testing not only the model of polarized gluons in the proton but also the model of spin-dependent fragmentation functions. However, it should be noted that the assumption on the spin-dependent fragmentation function might be somewhat too simple in the present analysis. In order to obtain more reliable prediction, further investigation on spin-dependent fragmentation functions is necessary. For the $\Lambda_b$ baryon production, similar analysis was performed by D. de Florian et. al [21]. Our analysis might be complementary to their analysis but more effective for extracting information of the polarized gluon in the proton, since the non-relativistic quark
model works better for $\Lambda_c^+$ ($D^{*+}$) than $\Lambda$ and furthermore the separation of gluon fusion and $q\bar{q}$ annihilation is easier for our processes.

Though the present calculation is confined to the leading order, the results are interesting and we hope that our analysis could be tested in the forthcoming RHIC experiments.

**Acknowledgment**

We would like to thank T. Iwata and N. Saito for useful discussions and comments on experimental feasibility. We are very much thankful to K. Sudoh and S. Oyama for interesting discussions and advice at early stage of this work. We thank K.
Sudoh for informing us a newly improved expression of eq.(12) for estimating statistical uncertainties. One (K.O.) of authors is grateful to T. Yamanishi, K. Sasaki and T. Ueda for giving him useful information related to this work. K. O. is supported by a Grant-in-Aid for Young Scientists (B) from the Ministry of Education, Culture, Sports, Science and Technology of Japan(#17740157).

REFERENCES

[1] J. Ashman et al. [European Muon Collaboration], Phys. Lett. B202 (1988) 603; Nucl. Phys. B328 (1989) 1.

[2] For a review see:
H. Y. Cheng, Int. J. Mod. Phys. A11 (1996) 5109;
B. Lampe and E. Reya, Phys. Rept. 332 (2000) 1;
H. Y. Cheng, Chin. J. Phys. 38 (2000) 753 [hep-ph/0002157].

[3] G. Bunce, N. Saito, J. Soffer and W. Vogelsang, Ann. Rev. Nucl. Part. Sci. 50 (2000) 525.

[4] S. Oyama, T. Morii and N. I. Kochelev, Phys. Rev. D 62 (2000) 057502 [Erratum-ibid. D 63 (2001) 079904];
K. Ohkuma and T. Morii, Mod. Phys. Lett. A 17 (2002) 1575.

[5] K. Ohkuma, K. Sudoh and T. Morii, Phys. Lett. B491 (2000) 117; [Erratum-ibid. B 543 (2002) 323].

Figure 7: The $D_{LL}$ for $\Lambda_c^+$ productions as a function of $\eta$ at $\sqrt{s}=200$ GeV(left panel) and $\sqrt{s}=500$ GeV(right panel)
[6] Bo Andersson, G. Gustafson, G. Ingelman and T. Sjostrand, Phys. Rept. 97 (1983) 31.

[7] B. Q. Ma, I. Schmidt, J. Soffer and J. J. Yang, Nucl. Phys. A 703 (2002) 346.

[8] J.A.M.Vermaseren, ”New features of FORM”, math-ph/0010025.

[9] J. Babcock, D. W. Sivers and S. Wolfram, Phys. Rev. D 18, (1978) 162.

[10] S. Eidelman et al. [Particle Data Group Collaboration], Phys. Lett. B 592 (2004) 1.

[11] Y. Goto et al. [Asymmetry Analysis Collaboration], Phys. Rev. D 62 (2001) 034017.

[12] M Glück, E. Reya, M. Stratmann and W. Vogelsang, Phys. Rev. D63 (2001) 094005.

[13] M. Glück, E. Reya and A. Vogt, Eur. Phys. J. C5 (1998) 461.

[14] C. Peterson, D. Schlatter, I. Schmitt and P. M. Zerwas, Phys. Rev. D27 (1983) 105.

See also
S. Kretzer and I. Schienbein, Phys. Rev. D59 (1999) 054004;
B. A. Kniehl and G. Kramer, hep-ph/0504058.

[15] D. Bortoletto et al. [CLEO Collaboration], it Phys. Rev. D37 (1988) 1719,
[Erratum-ibid. D39 (1989) 1471].

[16] T. J. V. Bowcock et al. [CLEO Collaboration], Phys. Rev. Lett. 55 (1985) 923;
See also
C.E.K. Charlesworth, A Study of the Decay Properties of the Charmed
Baryon Λ_c^+, Ph.D. thesis, University of Toronto (1992).

[17] A. Kotzinian, A. Bravar and D. von Harrach, Eur. Phys. J. C2 (1998) 329.

[18] A. Bartl, H. Fraas and W. Majerotto, Z. Phys. C6 (1980) 335.

[19] A. Airapetian et al. [HERMES Collaboration], Phys. Rev. D64 (2001) 112005.

[20] K. Sudoh, private communication. See also L. Rykov and K. Sudoh, hep-ph/0412244.
[21] D. de Florian, M. Stratmann and W. Vogelsang, *Phys. Rev. Lett.* 81 (1998) 530.