Semi-inclusive large–$p_T$ light hadron pair production as a probe of polarized gluons†

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Abstract

We propose a new formula for extracting the polarized gluon distribution $\Delta g$ in the proton from the large–$p_T$ light hadron pair production in deep inelastic semi-inclusive reactions. Though the process dominantly occurs via photon–gluon fusion (PGF) and QCD Compton, we can remove an effect of QCD Compton from the combined cross section of light hadron pair production by using symmetry relation among fragmentation functions and thus, rather clearly extract information of $\Delta g$.

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1 Introduction

Since the measurement of the polarized structure function of the proton $g_1^p$ for wide kinematic range of Bjorken $x$ and $Q^2$ by the EMC in 1988[1], the so-called proton spin puzzle has been still one of the most challenging topics in particle and nuclear physics. After the EMC experiment, much progress has been attained experimentally and theoretically.[2] A large amount of data on polarized structure functions of proton, neutron and deuteron were accumulated. The progress in the data precision is also remarkable. Furthermore, with much theoretical effort based on the next–to–leading order QCD analyses of the longitudinally polarized structure function $g_1$, a number of excellent parameterization models of the polarized part on distribution functions (pol–PDFs) were obtained from fitting to many/precise data with various targets for polarized deep inelastic scattering (pol–DIS) [3, 4, 5, 6]. All of these parameterization models tell us that quarks carry a little of the proton spin, i.e. only 30% or smaller. Due to an intense experimental and theoretical effort, a rather good knowledge of the polarized valence quark distribution has been obtained so far. However, knowledge of $\Delta g$ is still very limited. As is well-known, the next–to–leading order QCD analyses on $g_1$ bring about information on the first moment of the polarized gluon $\Delta g$.[7] However, there are large uncertainties in $\Delta g$ extracted from $g_1$ alone. To solve the so-called spin puzzle, it is very important to precisely know how the gluon polarizes in the nucleon.

So far, a number of interesting processes such as direct prompt photon production in polarized proton–polarized proton collisions[8], open charm[9] and $J/\psi$[10] productions in polarized lepton scattering off polarized nucleon targets, were proposed for studying longitudinally polarized gluon distributions. Recently, HERMES group at DESY reported the first measurement of the polarized gluon distribution from di–jet analysis of semi–inclusive processes in pol–DIS, though only one data point was given as a function of Bjorken $x$.[11] In general, a large–$p_T$ hadron pair is produced via photon–gluon fusion (PGF) and QCD Compton at the lowest order of QCD. The PGF gives us a direct information on the polarized gluon distribution in the nucleon, whereas QCD Compton is background to the signal process for extracting $\Delta g$.[12, 13] For the case of heavy hadron pair($D\bar{D}$, $D^*\bar{D}^*$, etc.) production, we could safely neglect the contribution of QCD Compton because the heavy quark content in the proton is extremely small and also the fragmenting probability of light quarks to heavy hadrons is very small. However, in this case the cross section itself is small at the energy in the running(HERMES) or forthcoming(COMPASS) experiments.
and thus, we could not have enough data for carrying out detailed analysis. For the case of light hadron pair production, we will have a rather large number of events because of large cross sections. However, in this case QCD Compton can no longer be neglected and hence, it looks rather difficult to unambiguously extract the behavior of $\Delta g$ from those processes.

In this work, to overcome these difficulties we propose a new formula for clearly extracting the polarized gluon distribution from the light hadron pair production of pol-DIS by removing the QCD Compton component from the cross section. As is well-known, the cross section of the hadron pair production being semi-inclusive process, can be calculated based on the parton model with various fragmentation functions. Then, by using symmetry relations among fragmentation functions and taking an appropriate combination of various hadron pair production processes, we can remove the contribution of QCD Compton from the cross section and thus, get clear information of $\Delta g$ from those processes. Here, to show how to do this practically, we consider the light hadron pair production with large transverse momentum.

2 A new formula for extracting $\Delta g(x)$ from large–$p_T$ pion pair production

Let us consider the process of $\ell + N \rightarrow \ell' + h_1 + h_2 + X$ in polarized lepton scattering off polarized nucleon targets, where $h_1$ and $h_2$ denote light hadrons in a pair. As mentioned above, the spin–dependent differential cross section at the leading order of QCD can be given by the sum of the PGF process and QCD Compton as follows,

$$d\Delta \sigma = d\Delta \sigma_{PGF} + d\Delta \sigma_{QCD},$$

with

$$d\Delta \sigma = d\sigma_{-+} - d\sigma_{++} + d\sigma_{+-} - d\sigma_{++},$$

where, for example, $d\sigma_{-+}$ denote that the helicity of an initial lepton and the one of a target proton is negative and positive, respectively. Each term on the right hand side of eq.(1) is given by

$$d\Delta \sigma_{PGF} \sim \Delta g(\eta, Q^2) d\Delta \sigma_{PGF} \sum_{i=\bar{u},d,s,\bar{u},\bar{d},\bar{s}} e_i^2 \{ D_{i}^{h_1}(z_1, Q^2) D_{i}^{h_2}(z_2, Q^2) + (1 \leftrightarrow 2) \},$$

$$d\Delta \sigma_{QCD}$$
where $\Delta g(\eta, Q^2)$, $\Delta f_q(\eta, Q^2)$ and $D^{h_i}_q(z, Q^2)$ denote the polarized gluon and the quark distribution function of $q$ with momentum fraction $\eta$ and the fragmentation function of a hadron $h_i$ with momentum fraction $z_i$ emitted from a parton $i$, respectively. $d\Delta \hat{\sigma}_{PGF}$ and $d\Delta \hat{\sigma}_{QCD}$ are the polarized differential cross sections of hard scattering subprocesses for $\ell g \rightarrow \ell' q\bar{q}$ and $\ell (\gamma) \rightarrow \ell' q\bar{q}$ at the leading order QCD, respectively.

Here we consider the following 4 pairs of the produced hadrons $h_1$ with $z_1$ and $h_2$ with $z_2$,

(i) $(\pi^+, \pi^-)$, (ii) $(\pi^-, \pi^+)$, (iii) $(\pi^+, \pi^+)$, (iv) $(\pi^-, \pi^-)$,

where (particle 1, particle 2) corresponds to ($h_1$ with $z_1$, $h_2$ with $z_2$). Then, the differential cross section of eq. (4) for each pair can be written as

(i) $d\Delta \sigma^{\pi^+\pi^-}$

$$d\Delta \sigma^{\pi^+\pi^-} \sim \Delta g(\eta, Q^2) d\Delta \hat{\sigma}_{PGF} \left\{ \frac{4}{9} D_{u^+}^+(z_1, Q^2) D_{u^-}^-(z_2, Q^2) + \frac{1}{9} D_{d^+}^+(z_1, Q^2) D_{d^-}^-(z_2, Q^2) 
+ \frac{1}{9} D_{s^+}^+(z_1, Q^2) D_{s^-}^-(z_2, Q^2) + (\pi^+(z_1) \leftrightarrow \pi^-(z_2)) \right\}$$

$$+ \frac{4}{9} \Delta u(\eta, Q^2) d\Delta \hat{\sigma}_{QCD} \left\{ D_{u^+}^+(z_1, Q^2) D_{g^-}^-(z_2, Q^2) + D_{u^-}^+(z_2, Q^2) D_{g^+}^+(z_1, Q^2) \right\}$$

$$+(\text{contributions from } \Delta d, \Delta s, \Delta \bar{u}, \Delta \bar{d} \text{ and } \Delta \bar{s})$$

(ii) $d\Delta \sigma^{\pi^-\pi^+}$

$$d\Delta \sigma^{\pi^-\pi^+} \sim \Delta g(\eta, Q^2) d\Delta \hat{\sigma}_{PGF} \left\{ \frac{4}{9} D_{u^-}^-(z_1, Q^2) D_{u^+}^+(z_2, Q^2) + \frac{1}{9} D_{d^-}^-(z_1, Q^2) D_{d^+}^+(z_2, Q^2) 
+ \frac{1}{9} D_{s^-}^-(z_1, Q^2) D_{s^+}^+(z_2, Q^2) + (\pi^-(z_1) \leftrightarrow \pi^+(z_2)) \right\}$$

$$+ \frac{4}{9} \Delta u(\eta, Q^2) d\Delta \hat{\sigma}_{QCD} \left\{ D_{u^-}^+(z_1, Q^2) D_{g^+}^-(z_2, Q^2) + D_{u^+}^+(z_2, Q^2) D_{g^-}^-(z_1, Q^2) \right\}$$

$$+(\text{contributions from } \Delta d, \Delta s, \Delta \bar{u}, \Delta \bar{d} \text{ and } \Delta \bar{s})$$

(iii) $d\Delta \sigma^{\pi^+\pi^+}$

$$d\Delta \sigma^{\pi^+\pi^+} \sim \Delta g(\eta, Q^2) d\Delta \hat{\sigma}_{PGF} \left\{ \frac{4}{9} D_{u^+}^+(z_1, Q^2) D_{u^+}^+(z_2, Q^2) + \frac{1}{9} D_{d^+}^+(z_1, Q^2) D_{d^+}^+(z_2, Q^2) 
+ \frac{1}{9} D_{s^+}^+(z_1, Q^2) D_{s^+}^+(z_2, Q^2) + (\pi^+(z_1) \leftrightarrow \pi^+(z_2)) \right\}$$

$$+ \frac{4}{9} \Delta u(\eta, Q^2) d\Delta \hat{\sigma}_{QCD} \left\{ D_{u^+}^+(z_1, Q^2) D_{g^+}^+(z_2, Q^2) + D_{u^+}^+(z_2, Q^2) D_{g^+}^+(z_1, Q^2) \right\}$$
Various fragmentation functions in eqs. (4)–(7) can be classified into the following 4 functions,\(^{14}\)

Due to the isospin symmetry and charge conjugation invariance of the fragmentation functions, the denominator of $$\Delta g/g$$

\[ \Delta g \equiv \Delta \sigma^\pi^-\pi^- \]

is dropped out from the numerator and

\[ \Delta \sigma^\pi^-\pi^- + (\text{contributions from } \Delta d, \Delta s, \Delta \bar{u}, \Delta \bar{d} \text{ and } \Delta \bar{s}) , \]

(iv)

\[
\begin{align*}
&d\Delta \sigma^\pi^-\pi^- \\
\sim & \Delta g(\eta, Q^2) \Delta \sigma_{PGF} \left\{ \frac{4}{9} D_u^\pi^+(z_1, Q^2) D_u^\pi^-(z_2, Q^2) + \frac{1}{9} D_d^\pi^+(z_1, Q^2) D_d^\pi^-(z_2, Q^2) \\
&+ \frac{1}{9} D_s^\pi^+(z_1, Q^2) D_s^\pi^-(z_2, Q^2) + (\pi^-(z_1) \leftrightarrow \pi^-(z_2)) \right\} \\
&+ \frac{4}{9} \Delta u(\eta, Q^2) d\Delta \sigma_{QCD} \left\{ D_u^\pi^-(z_1, Q^2) D_d^\pi^+(z_2, Q^2) + D_u^\pi^-(z_2, Q^2) D_d^\pi^+(z_1, Q^2) \right\} \\
&+ (\text{contributions from } \Delta d, \Delta s, \Delta \bar{u}, \Delta \bar{d} \text{ and } \Delta \bar{s}) . \end{align*}
\]

Due to the isospin symmetry and charge conjugation invariance of the fragmentation functions, various fragmentation functions in eqs. (4)–(7) can be classified into the following 4 functions,\(^{14}\)

\[ D \equiv D_u^+ = D_d^+ = D_s^+ = D_s^-, \quad \widetilde{D} \equiv D_u^- = D_d^+ = D_s^+ = D_s^-, \quad D_s \equiv D_s^+ = D_s^+ = D_s^- = D_s^-, \quad D_g \equiv D_2^+ = D_2^- , \]

where \( D \) and \( \widetilde{D} \) are called favored and unfavored fragmentation functions, respectively. Considering the suppression of the \( s \) quark contribution to the pion production compared with the \( u \) and \( d \) quark contribution, we do not identify \( D_s \) with \( \widetilde{D} \).\(^{15, 16}\)

By using these 4 kinds of pion fragmentation functions, we can make an interesting combination of cross sections which contains only the PGF contribution as follows;

\[\begin{align*}
d\Delta \sigma^\pi^+\pi^- &+ d\Delta \sigma^\pi^-\pi^+ - d\Delta \sigma^\pi^+\pi^- - d\Delta \sigma^\pi^-\pi^- \\
\sim & \frac{10}{9} \Delta g(\eta, Q^2) d\Delta \sigma_{PGF} \left\{ D(z_1, Q^2) - \widetilde{D}(z_1, Q^2) \right\} \left\{ D(z_2, Q^2) - \widetilde{D}(z_2, Q^2) \right\} .
\end{align*}\]

From this combination, we can calculate the double spin asymmetry \( A_{LL} \) defined by

\[
A_{LL} = \frac{d\Delta \sigma^\pi^+\pi^- + d\Delta \sigma^\pi^-\pi^+ - d\Delta \sigma^\pi^+\pi^- - d\Delta \sigma^\pi^-\pi^-}{d\sigma^\pi^+\pi^+ + d\sigma^\pi^-\pi^- - d\sigma^\pi^+\pi^- - d\sigma^\pi^-\pi^-} = \frac{\Delta g(\eta, Q^2)}{g(\eta, Q^2)} \cdot \frac{d\Delta \sigma_{PGF}}{d\sigma_{PGF}} ;
\]

where the factor of the fragmentation function in eq. (8) is dropped out from the numerator and the denominator of \( A_{LL} \).\(^{17}\)

Therefore, from the measured \( A_{LL} \), one can get clear information of \( \Delta g/g \) with reliable calculation of \( d\Delta \sigma_{PGF}/d\sigma_{PGF} \).\(^*\)

\(^*\)For large \( Q^2 \) regions, heavy quarks might contribute to the PGF and QCD Compton. Even so, the final form of eq. (8) for \( A_{LL} \) remains unchanged if \( D_Q^\pi^+ = D_Q^\pi^+ = D_Q^\pi^- = D_Q^\pi^- \).
3 Numerical calculation of cross section and double spin asymmetry

Now, let us calculate numerically the cross section and double spin asymmetry $A_{LL}$ for the large–$p_T$ pion pair production of pol–DIS. The spin–independent (spin–dependent) differential cross sections for producing hadrons $h_1$ and $h_2$ are given by\cite{17}

\[
\frac{d(\Delta)\sigma^{h_1 h_2}}{dz_1 d \cos \theta_1 dz_2 d \cos \theta_2 dx dy} = \frac{d(\Delta)\sigma^{h_1 h_2}_{PGF}}{dz_1 d \cos \theta_1 dz_2 d \cos \theta_2 dx dy} + \frac{d(\Delta)\sigma^{h_1 h_2}_{QCD}}{dz_1 d \cos \theta_1 dz_2 d \cos \theta_2 dx dy}.
\]

Each term in the right hand side of eq.(10) is written as

\[
\frac{d(\Delta)\sigma^{h_1 h_2}_{PGF}}{dz_1 d \cos \theta_1 dz_2 d \cos \theta_2 dx dy} = (\Delta)g(\eta, Q^2) C(\theta_1, \theta_2) \frac{d(\Delta)\sigma^{h_1 h_2}_{PGF}}{dz_1 d \cos \theta_1 dz_2 d \cos \theta_2 dx dy} \times \sum_{i=u,d,s,u,d,s} e_i^2 \{ D_i^{h_1}(\xi_1, Q^2) D_i^{h_2}(\xi_2, Q^2) + (1 \leftrightarrow 2) \},
\]

\[
\frac{d(\Delta)\sigma^{h_1 h_2}_{QCD}}{dz_1 d \cos \theta_1 dz_2 d \cos \theta_2 dx dy} = \sum_{q=u,d,s,u,d,s} \frac{d(\Delta)\sigma^{h_1 h_2}_{QCD}}{dz_1 d \cos \theta_1 dz_2 d \cos \theta_2 dx dy} \times \{ D_q^{h_1}(\xi_1, Q^2) D_q^{h_2}(\xi_2, Q^2) + (1 \leftrightarrow 2) \},
\]

where $\eta = x + (1 - x)\tau_1 \tau_2$, $Q^2 = xys$, $\xi_1 = \left( \frac{\alpha + \tau_2}{\tau_1} \right) z_1$, $\xi_2 = \left( \frac{\alpha + \tau_2}{\tau_1} \right) z_2$ and $C(\theta_1, \theta_2) = \frac{(\tau_1 + \tau_2)^2}{\eta \tau_1 \tau_2} \frac{1 - x}{8 \cos^2 \frac{\theta_1}{2} \cos^2 \frac{\theta_2}{2} \sin^2 \frac{1}{2}(\theta_1 + \theta_2)}$, with $\tau_{1,2} = \tan \frac{\theta_{1,2}}{2}$.

Here we simply assume the scattering angle of outgoing hadrons $\theta_{1,2}$ to be the same with the one of scattered partons in the virtual photon–nucleon c.m. frame. This assumption might not be unreasonable if observed particles are light hadrons with high energy. $s$ is the total energy square of the lepton scattering off the nucleon. $x$, $y$ and $z_{1,2}$ are familiar kinematic variables for semi–inclusive processes in DIS, defined as $x = \frac{Q^2}{2P \cdot q}$, $y = \frac{P \cdot q}{P \cdot \ell}$ and $z_{1,2} = \frac{P \cdot P_{1,2}}{P \cdot q}$, where $\ell$, $q$, $P$ and $P_{1,2}$ are the momentum of the incident lepton, virtual photon, target nucleon and outgoing hadrons, respectively. At the leading order of QCD, differential cross sections of hard scattering subprocesses, $\ell g \rightarrow \ell' q\bar{q}$ and $\ell (\gamma^*) q \rightarrow \ell' (\gamma^*) q\bar{q}$, with two outgoing partons in an opposite azimuth angle are given as\cite{18}

\[
\frac{d(\Delta)\sigma_{PGF(QCD)}}{dz_1 d \cos \theta_1 dz_2 d \cos \theta_2 dx dy df_\ell} \times B(\theta_1, \theta_2) e_\ell^2 e_i^2 (\Delta) M_{i,PGF(QCD)}^2 = \frac{1}{128\pi^2} \frac{\alpha_s^2 \alpha_s}{(P_0 \cdot \ell) Q^2} \frac{y(\eta - x)(1 - \eta)^2}{x},
\]

\[
\frac{d(\Delta)\sigma_{QCD}}{dz_1 d \cos \theta_1 dz_2 d \cos \theta_2 dx dy df_\ell} = \frac{1}{128\pi^2} \frac{\alpha_s^2 \alpha_s}{(P_0 \cdot \ell) Q^2} \frac{y(\eta - x)(1 - \eta)^2}{x},
\]
with
\[
\frac{1}{B(\theta_1, \theta_2)} = \sin(\theta_1 + \theta_2) \\
\times \left[ \frac{\{z_i(1-\eta) + (\eta-x)\} \sin \theta_1 + \{z_{i(g)}(1-\eta) + (\eta-x)\} \sin \theta_2}{\sin \theta_1 \sin \theta_2} \right],
\]
where $z_i$, $\bar{z}_i$ and $z_g$ are the momentum fraction of the outgoing parton $i$, $\bar{i}$ and $g$, respectively, to the incoming parton, and are given as $z_i = \frac{\tau_i}{\tau_1+\tau_2}$, $z_{i(g)} = \frac{\tau_i}{\tau_1+\tau_2}$.\[17\] The amplitude $|\langle \Delta \rangle M|^2_{PGF(QCD)}$ in eq.(13) is presented elsewhere\[19\].

By using these formulas and pion fragmentation functions\[15\], we have calculated the spin–dependent and spin–independent cross sections of the large–$p_T$ pion pair production and estimated the double spin asymmetry at the energy of COMPASS experiments.\[†\] Here, we have taken the AAC\[6\] and GS96\[4\] parameterizations at LO QCD as polarized parton distribution functions and GRV98\[20\] and MRST98\[21\] as unpolarized ones. At $\sqrt{s} = 13.7\text{GeV}$, $y = 0.75$, $Q^2 \geq 1\text{GeV}^2$ and $W^2 \geq 10\text{GeV}^2$ with kinematical values of $\theta_{1,2}$ and $z_{1,2}$ for the produced pion pair, the calculated results of the spin–independent (spin–dependent) differential cross sections and $A_{LL}$ are shown as a function of $\eta$ in Figs.1 and 2, respectively. In Fig.2, error was estimated by\[22\] $\delta A_{LL} = \frac{1}{A_c P_{VT}} \sqrt{\frac{1}{\Delta \sigma_1} + \frac{1}{\Delta \sigma_2}}$, where $A_c = \frac{d\sigma_1 - d\sigma_2}{d\sigma_1 + d\sigma_2}$ with $d\sigma_1 = d\sigma(\pi^+\pi^-) + d\sigma(\pi^-\pi^+)$ and $d\sigma_2 = d\sigma(\pi^+\pi^+) + d\sigma(\pi^-\pi^-)$. $L$ is the integrated luminosity and $P = P_B P_T f$, where $P_B, P_T$ are the polarization of beam and target, respectively, and $f$ is the dilution factor. Here we used $L = 2 \text{fb}^{-1}(150 \text{ days running})$, $P_B = 0.80$ and $P_T \cdot f = 0.25$. From Fig.2, one can see a big difference of the behavior of $A_{LL}$ depending on the models of $\Delta g/g$ and hence, we can extract the behavior of $\Delta g$ rather clearly from this analysis.

### 4 Summary and discussion

We proposed a new formula for extracting the polarized gluon distribution from the large–$p_T$ light hadron pair production in pol–DIS by taking an appropriate combination of hadron pair productions. Since the double spin asymmetry $A_{LL}$ for this combination is directly proportional to $\Delta g/g$, the measurement of this quantity is quite promising for getting rather clear information on the polarized gluon distribution in the nucleon.

The analysis can be applied also for the kaon pair or the proton pair production by considering the reflection symmetry along the V–spin axis, the isospin symmetry and charge conjugation
Figure 1: $\eta$ dependence of combined spin-independent and spin-dependent differential cross sections defined at the denominator and numerator, respectively, of eq.(9) as a function of $\eta$ at $\sqrt{s} = 13.7$ GeV, $y = 0.75$ for the deep inelastic regions ($Q^2 \geq 1$ GeV$^2$ and $W^2 \geq 10$ GeV$^2$) with kinematical values of $\theta_{1,2}, z_{1,2}$ for the produced pion pair.

Figure 2: $\eta$ dependence of $A_{LL}$ at $\sqrt{s} = 13.7$ GeV, $y = 0.75$ for kinematical values of $\theta_{1,2}, z_{1,2}$ for the produced pion pair. Solid line and dotted line are for AAC LO and GS96LO-C parameterization models, respectively. $\Delta g/g$ itself is also presented for both parameterization models.
invariance of the fragmentation functions.

The same combinations of cross sections for light hadron pair production were discussed for photoproduction by other people\cite{23}, while we studied the lepton-proton processes in deep inelastic region in this work. Both of those processes are useful for extracting $\Delta g$.

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