A new twist-3 analysis of the single transverse-spin asymmetry for pion and kaon production at RHIC

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Abstract. We present a new analysis for the single-transverse spin asymmetry (SSA) for the inclusive pion and kaon productions in the proton-proton collisions measured at RHIC. The framework we use is the collinear factorization in which SSA appears as a twist-3 observable resulting from the multiparton correlations in the hadrons. As a relevant multiparton correlation, we include all the contributions associated with the quark-gluon correlation functions in the transversely polarized proton, i.e., those from the soft-gluon-pole (SGP) and the soft-fermion-pole (SFP). We have found that the SGP contribution alone is insufficient to describe the observed RHIC \(A_N\) data and the inclusion of the SFP contribution plays an important role for the improved description of the data. In particular, \(P_T\)-dependence of \(A_N\) and \(A_N\) for \(K^-\) have been well described in our new analysis.

1. Introduction
The large single transverse-spin asymmetry (SSA) observed in the inclusive single-hadron production, \(p^+p \to hX (h = \pi, K \text{ etc}.)\), at RHIC\(^[1-3]\) plays a crucial role to reveal the multiparton correlations inside the nucleon. In the region of the large transverse momentum of the final hadron, \(P_T \sim Q \gg \Lambda_{\text{QCD}}\), the SSA is described as a twist-3 observable in the collinear factorization, connecting the SSA to the multiparton correlations directly\(^[4-9]\). In principle, multiparton correlations causing the SSA in \(p^+p \to hX\) exist both in the initial-state proton and the final-state hadron. Since the analytic formula for the latter effect is not available, we shall focus in this work on the effect of the quark-gluon correlations in the transversely polarized proton and see how the existing data are described by those effects.\(^1\) In the transversely polarized nucleon, there are two independent twist-3 quark-gluon correlation functions, \(G_F(x_1, x_2)\) and \(\tilde{G}_F(x_1, x_2)\), which are defined from the light-cone correlation function in the nucleon \(\sim \langle \bar{\psi} F^{\alpha+} \psi \rangle\), with \(\psi\) being the quark field and \(F^{\alpha+}\) the gluon’s field strength. (For the explicit definition of the correlation functions and their property, see\(^[6,7]\).) The variables \(x_{1,2}\) and \(x_2 - x_1\) denote, respectively, the longitudinal momentum fractions of the quarks and the gluon coming out of the nucleon. In the twist-3 mechanism, the complex phase necessary for SSA is supplied as a pole contribution from an internal propagator in the hard part. These poles are classified into the soft-gluon-pole (SGP) and soft-fermion-pole (SFP), corresponding,

\(^1\) The twist-3 fragmentation function for the final hadron is chiral-odd and appears in pair with the transversity distribution. We assume this chiral-odd effect may be small in this initial study.
respectively, to $x_i = 0$ ($i = 1$ or $2$) and $x_2 - x_1 = 0$. Accordingly, the single-spin-dependent cross section can be represented as

$$
\Delta \sigma^{tw3}_{p^+p^-hX} \sim \left( G_F(x, x) - x \frac{dG_F(x, x)}{dx} \right) \otimes f(x') \otimes D(z) \otimes \hat{\sigma}_{SGP} \\
+ \left( G_F(0, x) + \tilde{G}_F(0, x) \right) \otimes f(x') \otimes D(z) \otimes \hat{\sigma}_{SFP},
$$

(1)

where the first and the second term represents, respectively, the SGP and the SFP contributions, and $f(x')$ and $D(z)$ are the unpolarized parton distribution and the fragmentation functions.

Kouvaris et al. [5] derived $\hat{\sigma}_{SGP}$ in (1) and performed a numerical analysis of the existing $A_N$ data.  

They obtained a reasonable description of the RHIC data except for the positive asymmetry for the $K^-$ production and the $p_T$-dependence. One of the present authors derived the formula for $\hat{\sigma}_{SFP}$ [8] and found $\hat{\sigma}_{SFP} \gg \hat{\sigma}_{SGP}$ in the relevant channels, showing a potential importance of the SFP contribution.

In our recent paper [11], we have analyzed the RHIC $A_N$ data based on the formula (1) including both SGP and SFP contributions. We found that the inclusion of the SFP contribution gives a better description of the data and that the SFP contribution can not be replaced by the readjustment of the SGP contribution. This is the first numerical analysis showing the importance of the SFP effect. This talk provides a short summary of the analysis and some new plots not shown in [11].

2. Phenomenological analysis of RHIC $A_N$ data

2.1. Fitting

For the fitting, we have assumed the following functional form for the SGP and SFP functions,

$$
G_{F,a}(x, x) = N_a^{G,F} x^{\alpha_a G,F} (1 - x)^{\beta_a G,F} \hat{f}_a(x) \\
G_{F,a}(0, x) + \tilde{G}_{F,a}(0, x) = N_a^{F} x^{\alpha_a F} (1 - x)^{\beta_a F} \hat{f}_a(x),
$$

where the subscript $a$ denote the light-quark flavor, $a = u, d, s, \bar{u}, \bar{d}, \bar{s}$, and $N_a^{G,F}, \alpha_a^{G,F}$ and $\beta_a^{G,F}$ are the parameters to be determined by the fitting. For simplicity, the scale dependence of each twist-3 functions are assumed to be the same as the unpolarized quark distribution function $f_a(x)$ in the right-hand-side. In our fitting, we have included the RHIC data by the STAR [1,2] ($\sqrt{S} = 200$ GeV) and the BRAHMS [3] ($\sqrt{S} = 62.4$ GeV) collaborations. We did not use the FNAL data ($\sqrt{S} = 20$ GeV), since the NLO QCD in the collinear factorization fails to reproduce the unpolarized cross section at the fixed target energy.

Under this assumption, we have performed three types of fitting in order to see the importance of the SFP effect. FIT 1 includes both SGP and SFP contributions. FIT 2 omit the SFP contribution from FIT 1 with the same degrees of freedom as FIT 1 for the SGP contribution. FIT 3 includes only the SGP contribution but with more degrees of freedom for the parameters. For the fits, we used the GRV98 [12] parton distribution and the DSS fragmentation functions for $\pi$ and $K$ [13]. The obtained results are shown in Fig. 1 together with the RHIC data. For comparison we also showed the result by Kouvaris et al. (Fit II of [5]). One sees that FIT 1 and FIT 3 give good agreement with the data, while FIT 2 fails to reproduce $A_N$ for $K^-$ production. This feature is reflected in the values of $\chi^2/d.o.f$, which are 1.21, 2.46 and 1.32 for FIT 1, 2 and 3, respectively. Although FIT 3 reproduce the data, some of the obtained SGP functions in FIT 3 show an unphysical behavior, which causes large $A_N$ for $\pi$ in the small $x_F$ region at the FNAL energy. From these facts, we regard our FIT 1 as the best fit for the RHIC $A_N$ data.

2 For the origin of the combination $G_F(x, x) - x \frac{dG_F(x, x)}{dx}$ for the SGP contribution, see [10].
Fig. 1. Results of the analysis in comparison with the RHIC data [1–3].

Fig. 2. The obtained SGP and SFP functions in FIT 1 in comparison with the unpolarized parton distribution function scaled by 1/10.

Fig. 2 shows the SGP and SFP functions for each quark flavor in FIT 1. One sees from the figure that the SGP and the SFP functions have similar magnitude, but the SGP functions spreads more in the larger $x$ region, which plays an important role for the rising $A_N$ at large $x_F$. Among the SFP functions, those for the $u$ and $d$ quarks are larger and have longer range than those for other flavors.

2.2. $P_T$-dependence of the asymmetry

Another interesting feature of $A_N$ is its dependence on the transverse momentum ($P_T$) of the final hadron. Fig. 3 shows the calculated $P_T$-dependence of $A_N$ for $\pi^0$ together with the STAR data
(left figure) and that in the wider range of $P_T$ for FIT 1 (right figure). All three fits reproduce the $P_T$-dependence of the data. This is quite natural since our fit used the corresponding $P_T$ values for each data point shown in Fig. 1, and thus the $P_T$-dependence shown in Fig. 3 is partly taken into account. At larger $P_T$, $A_N$ starts decreasing but not as fast as $\sim M_N/P_T$. This is because two effects of $O(M_N P_T/(\sim T))$ and $O(M_N P_T/(\sim U))$ coexist in $A_N$ reflecting its twist-3 nature, which leads to rather flat $P_T$-behavior at moderate values of $x_F$. At $x_F = 0$, $A_N$ stays zero in the whole $P_T$ region which is consistent with the PHENIX data [14].

Figure 3. $P_T$-dependence of $A_N^{\pi^0}$ compared with the STAR data [2] (left), and the $P_T$-dependence of $A_N^{K^0}$ in the large $P_T$ region for FIT 1 (right).

2.3. Role of the SFP contribution and the flavor decomposition

By separating the calculated $A_N$ into the SGP and the SFP contributions, we found that a major contribution comes from the former effect. However, the SFP contribution also brings a large contribution at $x_F \leq 0.3$ which cancels the SGP contribution, making $A_N$ small in this region. For $K^-$ and $\pi^-$, we found a significant contribution from the SFP effect. For the detail, see Fig. 4 in [11].

To see more detail of FIT 1, we have shown in Fig. 4 the decomposition of $A_N$ at $x_F \geq 0.4$ for $\pi^\pm$ and $K^\pm$ into each quark-flavor of the quark-gluon correlation functions. As is seen from the figure, the dominant contribution comes from the SGP effect for the valence flavor. However, for $K^\pm$, the SFP effect from $u$- and $d$-quark flavors is also significant. This is because of the corresponding large SFP functions (see Fig. 2) and the large partonic hard cross section in the gluon-fragmentation channel combined with the large gluon component for $K$ in the DSS fragmentation function. For the pion, this SFP effect in the gluon-fragmentation channel is canceled by the quark contributions, making the net SFP effect small.

3. Conclusion and outlook

In this work we have presented a new analysis of the RHIC $A_N$ data for $\pi$ and $K$ based on the twist-3 mechanism, including the complete contributions from the quark-gluon correlation functions in the transversely polarized nucleon. We have found that the SGP contribution alone is insufficient and the inclusion of the SFP contribution is crucial to reproduce all the reported RHIC data. The SGP and the SFP functions determined in our analysis can be used to predict the SSA in other processes such as the direct-photon production and Drell-Yan process at RHIC, and semi-inclusive deep inelastic scattering at EIC energy, and should be tested by confrontation with experimental data.

In our present study, other twist-3 effects, i.e., the three-gluon correlations in the transversely polarized proton and the contribution from the twist-3 fragmentation function, have not been
Flavor decomposition of $A_N$ for the charged meson production in FIT 1. The solid and dashed lines show the contributions from the SGP and SFP components, respectively.

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