SINGLE-SPIN ASYMMETRIES AND SOFT-GLUON POLES

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Mechanism for the single transverse spin asymmetries in the pion production, \( p^+ + p' \rightarrow \pi(\ell_T) + X \), and the \( \Lambda \) hyperon polarization, \( p + p' \rightarrow \Lambda^0(\ell_T) + X \), is investigated in the framework of QCD factorization theorem. We identify all the soft-gluon pole contributions coming from the twist-3 distribution and/or fragmentation functions and show that they give rise to large asymmetries at large \( x_F \).

1 Introduction

The interest in the single transverse spin asymmetry \( A_N \) in the pion production, \( N(P, S_\perp) + N(P') \rightarrow \pi(\ell_T) + X \), and the hyperon (typically \( \Lambda \)) polarization \( P_\Lambda \) in the unpolarized \( NN \) collision, \( N(P) + N(P') \rightarrow \Lambda(\ell_T, S_\perp) + X \), resides in the fact that they probe quark-gluon correlation in the hadrons (higher twist effect) which is not included in the parton model. Without it, the partonic cross sections are strongly suppressed by \( m_q/Q \) (where \( m_q \) is a quark mass and \( Q \) is a hard scale involved) and gives negligible asymmetries.

In this talk, I will discuss \( A_N \) and \( P_\Lambda \) in the framework of the collinear factorization. According to the generalized QCD factorization theorem, the cross section for \( A_N \) typically consists of three kinds of twist-3 cross sections,

(A) \[ G_a(x_1, x_2) \otimes q_b(x') \otimes \hat{q}_{c \rightarrow \pi}(z) \otimes \hat{\sigma}_{ab \rightarrow c}, \]

(B) \[ \delta q_a(x) \otimes E_b(x_1', x_2') \otimes \hat{q}_{c \rightarrow \pi}(z) \otimes \hat{\sigma}_{ab \rightarrow c}, \]

(C) \[ \delta q_a(x) \otimes q_b(x') \otimes \tilde{E}_{c \rightarrow \pi}(z_1, z_2) \otimes \tilde{\sigma}_{ab \rightarrow c}, \]

and \( P_\Lambda \) likewise receives two contributions,

(A') \[ E_a(x_1, x_2) \otimes q_b(x') \otimes \delta q_{c \rightarrow \Lambda}(z) \otimes \delta_{ab \rightarrow c}, \]

(C') \[ q_a(x) \otimes q_b(x') \otimes \tilde{G}_{c \rightarrow \Lambda}(z_1, z_2) \otimes \tilde{\sigma}_{ab \rightarrow c}. \]

Here the functions with two variables (momentum fractions) \( G_a(x_1, x_2) \), \( E_a(x_1, x_2) \), \( \tilde{E}_{c \rightarrow \pi}(z_1, z_2) \), \( \tilde{G}_{c \rightarrow \Lambda}(z_1, z_2) \) are twist-3 quantities: \( G_a \) and \( E_a \) are, respectively, the transversely polarized distribution and the unpolarized distribution functions in the nucleon. The functions with a hat, \( \tilde{E}_{c \rightarrow \pi} \) and \( \tilde{G}_{c \rightarrow \Lambda} \) are, respectively, the unpolarized fragmentation function for the pion and the transversely polarized fragmentation function for the \( \Lambda \) hyperon.

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polarized fragmentation function for $\Lambda$. $a$, $b$ and $c$ stand for the parton’s species. Other functions are twist-2; $q_b(x)$ the unpolarized distribution (quark or gluon), $\delta q_a(x)$ the transversity distribution, $\hat{q}_{c\to \pi}$ the unpolarized fragmentation function and $\delta \hat{q}_{c\to \Lambda}$ the transversity fragmentation function for $\Lambda$. $\delta_{ab\to c}$ etc represents the partonic cross section for the process $a + b \to c + \text{anything}$ which yields large transverse momentum of the parton $c$. Note that $\delta q_a$, $E_a$, $\delta \hat{q}_{c\to \Lambda}$ and $\hat{E}_{c\to \pi}$ are chiral-odd, and (B), (C) and (A’) contain two chiral-odd functions, which should appear in a pair along a fermion line in the diagram for the cross sections.

2 Twist-3 distribution and fragmentation functions

Relevant twist-3 distributions are defined from a quark-gluon correlation in the nucleon

$$M_{Fij}^a(x_1, x_2) = \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2 - x_1)} (PS)\bar{\psi}_j(0) gF^{\alpha+}(\mu n) \psi_i(\lambda n)|PS\rangle\langle 0|,$$

and they are classified in eqs.(7)-(9) of Ref. Likewise the twist-3 fragmentation functions are defined from

$$\tilde{M}_{Fij}^a(z_1, z_2) = \sum_x \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{-i\lambda z_1} e^{-i\mu(1/z_2 - 1/z_1)}$$

$$\times (0|\psi_i(0)|HX\rangle \langle HX| gF^{\alpha\beta}(\mu n) n_\beta \bar{\psi}_j(\lambda n)|0). \quad (7)$$

Similarly to $M_{Fij}^a(x, y)$, $\tilde{M}_{Fij}^a(z_1, z_2)$ is decomposed to define twist-3 fragmentation functions as

$$\tilde{M}_{Fij}^a(z_1, z_2) = M/4\psi_c S_{a\perp} \tilde{G}_F(z_1, z_2)/z_2 - i M/4\gamma_5 S_{a\perp} \tilde{G}_F^5(z_1, z_2)/z_2$$

$$- i M(S \cdot n)/4\gamma_5 (p^a \cdot \bar{\psi}_j - \gamma^a \bar{\psi}_j) \tilde{H}_F(z_1, z_2)/z_2$$

$$+ M/4\gamma_5 \bar{\psi}_j \gamma^a e^{a\alpha\beta} \tilde{E}_F(z_1, z_2)/z_2 + \cdots, \quad (8)$$

where $\cdots$ stands for the twist higher than 3. In [7], if one shifts the gluon field strength $gF^{\alpha\beta}(\mu n) n_\beta$ into the matrix element with $\psi(0)$ and call it $\tilde{M}_{Fij}^a(z_1, z_2)$, similar decomposition of $\tilde{M}_{Fij}^a(z_1, z_2)$ defines another fragmentation functions ($\tilde{G}_F$, $\tilde{G}_F^5$, $\tilde{H}_F$, $\tilde{E}_F$) by the hermiticity. In addition if we assume naive time reversal invariance, these functions become real and obey the relation $\tilde{G}_{FR}(z_1, z_2) = \tilde{G}_F(z_2, z_1)$, $\tilde{E}_{FR}(z_1, z_2) = \tilde{E}_F(z_2, z_1)$, $\tilde{G}_{F^5R}(z_1, z_2) = -\tilde{G}_F^5(z_2, z_1)$, $\tilde{H}_{FR}(z_1, z_2) = -\tilde{H}_F(z_2, z_1)$. We assume this symmetry property in our analysis.
3 Result for the asymmetries

With the complete set of the distribution and fragmentation functions up to twist-3, one can derive the cross section formula corresponding to (1)-(5). We follow the previous analyses Ref. 1 - Ref. 5 and employ the valence-quark soft-gluon approximation to analyze the cross section. In this approximation we keep only the terms with the derivative of the twist-3 functions such as \( \frac{dE_F(x,x)}{dx} \) and \( \frac{d\hat{E}_F(z,z)}{dz} \). This approximation should be valid at large \( x_F \to 1 \), which probe the region with large \( x \), small \( x' \) and large \( z \) in (1)-(5) where the relations such as \( |dE_F(x,x)/dx| >> E_F(x,x) \) and \( |d\hat{E}_F(z,z)/dz| >> \hat{E}_F(z,z) \) hold. The (B) term for \( A_N \) may cause enhancement in the asymmetry at \( x_F \to -1 \), but it turns out that it is negligible in all kinematic region because of the smallness of the hard cross section \( \hat{\sigma}^2 \) (Ref. 4).

To get a rough feeling on how each term for \( A_N \) and \( P_\Lambda \) behaves, we show the (C) term for \( A_N \) in Fig.1, and (A') and (C') term for \( P_\Lambda \) in Fig. 2. We use the same distribution and fragmentation functions used in Refs. 4, 5. For the twist-3 functions, we make an extension of the ansatz taken in Ref. - Ref. G_F^a(x,x) = K_\alpha q^a(x), E_F^a(x,x) = K'_\alpha \delta q^a(x), \hat{G}_F^a(x,x) = \tilde{K}_\alpha \hat{q}^a(x), \hat{E}_F^a(x,x) = \tilde{K}'_\alpha \hat{q}^a(x), and set \( K_u = -K_d = 0.07, K'_u = \tilde{K}_u = K_u \), and \( \tilde{K}'_d = 0.19 \). This choice of \( \tilde{K}'_a \) is simply motivated to reproduce \( A_N \) approximately at large \( x_F \).

One sees from Fig.1 that the (C) term alone can give equally good fit to the E704 data as the (A) term studied in Ref. 2. The (C') contribution also

![Figure 1: (C) contribution to \( A_N \) for \( \pi^{\pm,0} \).](image-url)
gives rise the rising behavior of $P_\Lambda$ at large $x_F$.

To summerize, we have presented an analysis for $A_N$ and $P_\Lambda$ in the framework of QCD factorization, in particular, the soft gluon-pole contribution with the twist-3 fragmentation functions is identified. With a moderate model assumption for the twist-3 fragmentation functions, derivative of the twist-3 fragmentation function also gives the rising behavior of the asymmetry at large $x_F$.

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