Spin asymmetry at large \( x_F \) and \( k_\perp \)

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Abstract. We suggest that the large single spin asymmetries observed at high momentum fractions \( x_F \) and transverse momenta \( k_\perp \) of the pion in \( p^+ p \rightarrow \pi(x_F, k_\perp) + X \) arise from the coherence of the soft interactions with the hard parton scattering process. Such coherence can be maintained if \( x_F \rightarrow 1 \) as \( k_\perp \rightarrow \infty \), while \( k_\perp^2 (1 - x_F) \sim \Lambda_{QCD}^2 \) stays fixed. Analogous coherence effects have been seen experimentally in the Drell-Yan process at high \( x_F \). We find that the \( p^+ p \rightarrow \pi X \) production amplitudes have large dynamic phases and that helicity flip contributions are unsuppressed in this limit, giving rise to potentially large single spin asymmetries.

1. Introduction and motivation

Single spin asymmetry (SSA) is the dependence of a cross section on a single measured spin. The size of a transverse SSA is characterized by the analyzing power

\[
A_N = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \propto \text{Im} [\mathcal{M}^- \mathcal{M}^+] \tag{1}
\]

where \( \mathcal{M}^- \) refers to the transverse spin (helicity) of the polarized particle. Sizeable \( A_N \)'s have been observed in \( p^+ p \rightarrow \pi(x_F, k_\perp) + X \) [1,2] and in \( pp \rightarrow \Lambda^1(x_F, k_\perp) + X \) [3]. At the highest measured longitudinal momentum fractions \( x_F \simeq 0.8 \) of the pion in \( p^+ p \rightarrow \pi^\pm X \) at the E704 experiment [1] (\( \sqrt{s} = 20 \) GeV) the asymmetry rises to \( |A_N| \sim 0.4 \), and increases for transverse momenta above \( k_\perp = 0.7 \) GeV. These asymmetries are an order of magnitude larger than those observed in DIS (\( ep^+ \rightarrow e + X \)) [4]. Recently the asymmetry has been seen to persist at much larger center of mass energy \( \sqrt{s} = 200 \) GeV in \( \pi^0 \) production at STAR [2]. The asymmetry increases with \( k_\perp \) up to \( k_\perp \simeq 2.5 \text{ GeV} \) for all available \( x_F = 0.25 \ldots 0.56 \).

From (1) we see that a sizeable \( A_N \) requires a helicity flip and a large (dynamical) phase between the two helicity amplitudes. Due to these requirements \( A_N \) vanishes the standard leading twist collinear QCD factorization [5] but can be described by using generalized schemes. The observed \( x_F \) dependence of \( A_N \) both at E704 and at STAR has been successfully fitted using transverse momentum dependent factorization [6] and including twist-three effects [7]. However, these approaches predict that \( A_N \sim \Lambda_{QCD}^2 / k_\perp \) in apparent conflict with the data.

Notice that largest asymmetries have been observed at very large \( x_F \simeq 0.8 \) values of pion momentum fraction in \( p^+ p \rightarrow \pi(x_F, k_\perp) + X \). In order to produce such a pion within the standard leading twist QCD factorization one quark must carry a momentum fraction \( x \gtrsim 0.9 \) of the proton and transfer a fraction \( z \gtrsim 0.9 \) of its momentum to the pion. These stringent

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requirements imply a very small production cross section. In fact, QCD at leading twist was found to underestimate the pion production cross section measured by E704 by an order of magnitude at high $x_F$ [8] which casts doubt on the applicability of factorization based approaches on SSAs in this kinematic region. On the other hand, the cross section measured at higher $\sqrt{s}$ and lower $x_F$ by STAR is consistent with leading twist QCD.

2. Coherence at large $x_F$

As noted above present approaches fail to produce the total cross section at large $x_F$ and the $k_{\perp}$ dependence of $A_N$ in $p^+p \to \pi(x_F, k_{\perp}) + X$. These shortcomings motivate us to suggest that the asymmetry is a large $x_F$ coherence effect [9]. Such effects in unpolarized Drell-Yan have been studied previously [10]. The angular distribution of the muon pair in $\pi N \to \mu\mu(x_F) + X$ provides a clear signature of the coherence effects which set in at high $x_F$. When the intrinsic hardness of the contributing pion Fock states becomes comparable to the virtuality $Q^2$ of the photon the angular distribution of the muons, which is $1 + \cos^2 \theta$ at leading twist, turns into $\sin^2 \theta$. This phenomenon was subsequently observed in the Drell-Yan data [11] where the change of angular distribution occurs at $x_F \simeq 0.7$ for $Q^2 \simeq 20$ GeV$^2$.

In general, the increase of coherence effects at large $x_F$ can be understood as follows (see [12]). The lifetime $\tau$ of a Fock state inside a rapidly moving proton is the inverse of the (light-front) energy difference $\Delta E$ between the Fock state and the proton

$$P^+\Delta E = M^2 - \sum_i k_{i,\perp}^2 + m_i^2/x_i, \quad \sum x_i = 1$$

where $x_i(>0)$, $k_{i,\perp}$, and $m_i$ are the momentum fraction, the transverse momentum, and the mass of parton $i$, respectively, $P^+$ is the proton light-front momentum, and $M$ is the proton mass. When one quark carries a large $x_i \sim x_F \to 1$ all other partons must have $x_j \sim 1-x_F \to 0$. Hence the lifetime of the state $\tau \sim 1/\Delta E \sim (1-x_F)P^+/\Lambda_{QCD}^2$ becomes short. The incoherence of such state with a hard quark requires $(1-x_F)P^+/\Lambda_{QCD}^2 \gg \tau_{\text{hard}} \sim P^+/k_{\perp}^2$ or $k_{\perp}^2(1-x_F) \gg \Lambda_{QCD}^2$. When $x_F$ grows large enough, i.e.,

$$k_{\perp}^2(1-x_F) \sim \Lambda_{QCD}^2,$$

the hard scattering becomes coherent with the soft physics and factorization is lost.

3. Coherence effects in $p^+p \to \pi X$

Sizeable coherence effects were observed in Drell-Yan for $x_F \simeq 0.8$ and for much larger photon virtuality $Q \simeq 4-5$ GeV than the typical $k_{\perp} \sim 1$ GeV of the pion at E704. Hence coherence is expected to be significant in the kinematic region of E704 where the asymmetries are large. We study the coherence effects in $p^+p \to \pi X$ in a similar manner as in Drell-Yan above. We take the scale $\sim k_{\perp}$ of perturbative QCD to be large, $k_{\perp} \to \infty$, but we keep $k_{\perp}^2(1-x_F)$ fixed (instead of $x_F$) so that (3) holds. In this limit single quark factorization fails and several partons from the same parent hadron contribute coherently to the process.

A leading contribution to the process in the limit of fixed $k_{\perp}^2(1-x_F)$ is shown in figure 1. A short lived Fock state with one fast quark ($x \sim 1$) is created via gluon exchange. The fast quark scatters with the target obtaining a large transverse momentum $k_{\perp}$. The quark finally picks up a slow antiquark and the pion is formed through a gluon exchange which equalizes the momentum fractions. The interactions within the slow quark system (indicated by the dashed circle in figure 1) are soft with momentum scale $\sim \Lambda_{QCD}$. The condition (3) implies that all parts of the diagram are fully coherent.

Recall that we need a helicity flip and a large, helicity-dependent phase to create a sizeable asymmetry. As a helicity flip is suppressed in the hard interactions, the flip must occur in
the soft subprocesses. This is modeled in figure 1 by helicity changing one gluon exchange. The helicity flip vertex is indicated by a dot and \( \pm \) are the helicities of the quarks in the two interfering amplitudes. A dynamical phase is obtained from the hard subprocess as indicated by the vertical dashed cut.

Using some further simplifications the two helicity amplitudes of figure 1 can be estimated [9]. A sizeable helicity dependent phase indeed arises when the coherence condition (3) is satisfied. This is a proof of principle that large \( A_N \) is possible in the kinematic limit of fixed \( k_\perp^2 (1 - x_F) \).

4. Conclusion
We demonstrated that large \( x_F \) coherence effects may explain the large asymmetries of \( p^+ p \to \pi X \). In the limit of large \( k_\perp \) with \( k_\perp^2 (1 - x_F) \) fixed the overall coherence of the scattering process is maintained which leads to large dynamical phases and possibly to large single spin asymmetries. Our mechanism is supported by the experimental result that \( A_N \) increases with \( k_\perp \) up to \( k_\perp \simeq 2 - 3 \) GeV. We expect that the maximum of \( A_N \) as a function of \( k_\perp \) is set by the coherence requirement (3) whence it is shifted from the standard expectation \( k_{\perp,\text{max}} \sim \Lambda_{QCD} \) to a slightly larger value.

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References
[1] Adams D L et al. (E704) 1991 Phys. Lett. B261 201–206
[2] Adams J et al. (STAR) 2004 Phys. Rev. Lett. 92 171801 (Preprint hep-ex/0310058)
[3] Surrow B (STAR) 2007 AIP Conf. Proc. 915 293–300 (Preprint arXiv:0705.3483 [hep-ex])
[4] Bunce G et al. 1976 Phys. Rev. Lett. 36 1113–1116
[5] Lundberg B et al. 1989 Phys. Rev. D40 3557–3567
[6] Airapetian A et al. (HERMES) 2005 Phys. Rev. Lett. 94 012002 (Preprint hep-ex/0408013)
[7] Kane G L, Pumpkin J and Reppio W 1978 Phys. Rev. Lett. 41 1689
[8] Anselmino M, Boglione M and Murgia F 1995 Phys. Lett. B362 164–172 (Preprint hep-ph/9503290)
[9] D’Alesio U and Murgia F 2004 Phys. Rev. D70 074009 (Preprint hep-ph/0408092)
[10] Qiu J W and Sterman G 1999 Phys. Rev. D59 014004 (Preprint hep-ph/9806396)
[11] Kouvaris C, Qiu J W, Vogelsang W and Yuan F 2006 Phys. Rev. D74 114013 (Preprint hep-ph/0609238)
[12] Bourrely C and Soffer J 2004 Eur. Phys. J. C36 371–374 (Preprint hep-ph/0311110)
[13] Hoyer P and Järvinen M 2007 JHEP 02 039 (Preprint hep-ph/0611293)
[14] Berger E L and Brodsky S J 1979 Phys. Rev. Lett. 42 940–944
[15] Anderson K J et al. 1979 Phys. Rev. Lett. 43 1219
[16] Falciano S et al. (NA10) 1986 Z. Phys. C31 513
[17] Brodsky S J, Hoyer P, Mueller A H and Tang W K 1992 Nucl. Phys. B369 519–542