Novel Spin Effects in QCD*

Stanley J. Brodsky, SLAC
RIKEN BNL Research Center
RHIC High P_T Workshop, December 2003

Measurements from HERMES, SMC, and Jlab show a significant single-spin asymmetry in semi-inclusive pion leptonproduction $\gamma^*(q)p \rightarrow \pi X$ when the proton is polarized normal to the photon-to-pion production plane. Hwang, Schmidt, and I [1] have shown that final-state interactions from gluon exchange between the outgoing quark and the target spectator system lead to such single-spin asymmetries at leading twist in perturbative QCD; *i.e.*, the rescattering corrections are not power-law suppressed at large photon virtuality Q^2 at fixed x_{bj} . The existence of such single-spin asymmetries (the Sivers effect) requires a phase difference between two amplitudes coupling the proton target with $J_p^z = \pm \frac{1}{2}$ to the same final-state, the same amplitudes which are necessary to produce a nonzero proton anomalous magnetic moment. The single-spin asymmetry which arises from such final-state interactions is in addition to the Collins effect which measures the transversity distribution $\delta q(x, Q)$. The Sivers effect also leads to a leading-twist target single-spin asymmetry for jet production in electroproduction where the thrust axis is used to define the production plane.

More generally, Hoyer, Marchal, Peigne, Sannino, and I [2] have shown that one cannot neglect the interactions which occur between the times of the currents in the current correlator even in light-cone gauge. For example, the final-state interactions lead to the Bjorken-scaling diffractive component $\gamma^*p \rightarrow pX$ of deep inelastic scattering. Since the gluons exchanged in the final state carry negligible k^+ , the Pomeron structure function closely resembles that of the primary gluon. The diffractive scattering of the fast outgoing quarks on spectators in the target in turn causes shadowing in the DIS cross section. These effects highlight the unexpected importance of final- and initial-state interactions in QCD observables—they lead to leading-twist single-spin asymmetries, diffraction, and nuclear shadowing, phenomena not included in the light-front wavefunctions of the target computed in isolation. Alternatively, as discussed by Belitsky, Ji, and Yuan [3], one can augment the light-front wavefunctions by including the phases induced by initial and final state interactions. Such wavefunctions correspond to solving the light-front bound state equation in an external field. Similar initial and final state interactions also lead to Sivers-type single-spin asymmetries in Drell-Yan processes and inclusive hadron reactions such as $pp \uparrow \rightarrow \pi X$, and heavy quark production, processes which will be important to study in polarized proton experiments at RHIC.

- [1] S. J. Brodsky, P. Hoyer, N. Marchal, S. Peigne and F. Sannino, Phys. Rev. D **65**, 114025 (2002) [arXiv:hep-ph/0104291].
- [2] S. J. Brodsky, D. S. Hwang and I. Schmidt, Phys. Lett. B **530**, 99 (2002) [arXiv:hep-ph/0201296].
- [3] A. V. Belitsky, X. Ji and F. Yuan, arXiv:hep-ph/0208038.

* Work supported by the Department of Energy, contract DE-AC03-76SF00515.
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Unexpected Role of Final State Interactions in Deep Inelastic Scattering

gluon exchange
after photon scs
not in LF WF

- * Single-spin asymmetry $\vec{S}_p \cdot \vec{q} \times \vec{p}_q$
Bjorken-scaling
- * Diffraction at Leading Twist
- * Nuclear Shadowing (interference of diff channels)
- * Energy Loss , p_T Broadening

Diffraction, Nuclear Shadowing, Pomeron
not in nuclear wavefunction!

* $\Delta L_{\text{Ioffe}} = \frac{2\nu}{Q^2} = \frac{1}{M \times B_1}$

Explicit Calculation $\rightarrow$ FSI

BHAPS

$q^+ \leq 0$
frame

LFTOPT: gluon exchanged after photon sets

Find non-zero leading-twist FSI effect

Leading twist diffraction, Eikonal form

Shadowing correction, not Coulomb phase

Gauge-independent:

Checked: Feynman, LCG [$A^+ = 0$] $\begin{cases} \text{ML} \\ \text{PV} \\ k \end{cases}$ prescriptions

Lesson for LCG:

$$g^{\mu\nu} = \frac{n^\mu k^\nu + k^\mu n^\nu}{n \cdot k}$$

At pole: $n \cdot k = k^+ = 0(\frac{1}{v})$.

Explicit calculation of FSI SSA

D.S. Huang

I.A. Schmitt

SAB

hep/ph/0201296

Collins, X. Ji, Burkhardt

Overlap of wavefunctions with

$$\Delta L_2 = 1$$

$$[e^{i(\kappa_1 - \kappa_2)}]$$

$\kappa_1 - \kappa_2$: IR Finite

$$i \vec{S}_p \cdot \vec{q} \times \vec{P}_q = i \vec{S}_p \cdot \vec{q} \times \vec{r}$$

$$\vec{P}_q = \vec{q} + \vec{r}$$

Approximate
at large r_1

$$P_y = A_n \approx \frac{\alpha_s(r_1^2) x_B M |r_1^2| \ln r_1^2}{r_1^2 + M^2}$$

Bjorken scaling for finite r_1

Same matrix elements as $q_p = F_2(0)$

Single-Spin Asymmetry in $P\bar{P}$ collisions

$$i \vec{S}_P \cdot \vec{P}_\pi \times \vec{P}$$

T-odd Sivers Effect

Jet Asymmetry

use thrust axis

$$i \vec{S}_P \cdot \vec{P}_{jet} \times \vec{P}$$

Analog Effect in DIS

$$i \vec{S}_P \cdot \vec{P}_{jet} \times \vec{q}$$

Leading Twist
BKS

$$i \vec{S}_P \cdot \vec{P}_{jet_A} \times (\vec{P}_{jet_B} - \vec{P})$$

Leading Twist