Single Spin Asymmetries and Higher Twist

George Sterman, *Institute for Theoretical Physics, SUNY Stony Brook*

Single spin asymmetries in single-particle inclusive cross sections have been observed at moderately large transverse momenta [1]. Nevertheless, they must vanish as $1/p_T$ at high energies. This may be seen directly from QCD factorization theorems, taking into account all possible twist-2 parton distributions. For these cross sections, we are therefore led to a twist-3 analysis. The relevant factorization theorem in this case is [2, 3]

$$\begin{aligned}
\Delta\sigma_{A+B\to\pi}(\vec{s}_T) &= \sum_{abc} \phi^{(3)}_{a/A}(x_1, x_2, \vec{s}_T) \otimes \phi_{b/B}(x') \otimes \hat{\sigma}_{a+b\to c}(\vec{s}_T) \otimes D_{c\to\pi}(z) \\
&\quad + \sum_{abc} \delta q_{a/A}(x, \vec{s}_T) \Big\{ \otimes \phi_{b/B}(x') \otimes \hat{\sigma}'_{a+b\to c}(\vec{s}_T) \otimes D^{(3)}_{c\to\pi}(z, z') \\
&\qquad + \otimes \phi^{(3)}_{b/B}(x'_1, x'_2) \otimes \hat{\sigma}''_{a+b\to c}(\vec{s}_T) \otimes D_{c\to\pi}(z) \Big\} .
\end{aligned}$$

$\phi^{(3)}_{a/A}(x'_1, x'_2, s_T)$ represents the possible twist-3 spin-dependent parton distributions, while $\delta q_{a/A}$ is the spin-dependent, chiral-odd, twist-2 transversity distribution [4], which must be paired in this case with a twist-3 chiral-odd fragmentation function $D^{(3)}$ or spin-independent parton distribution $\phi^{(3)}$, as shown.

For a number of reasons, we have suggested [3] that the dominant contribution to the asymmetry at large transverse momentum is associated with the matrix element

$$\begin{aligned}
T^{(V)}_{F_a}(x_1, x_2, s_T) &= \int \frac{dy_1^- dy_2^-}{4\pi} e^{ix_1 P^+ y_1^- + i(x_2 - x_1) P^+ y_2^-} \\
&\quad \times \langle P, \vec{s}_T | \bar{\psi}_a(0) \gamma_+ \left[\epsilon^{s_T \sigma n \bar{n}} F_{\sigma +}(y_2^-) \right] \psi_a(y_1^-) | P, \vec{s}_T \rangle ,
\end{aligned}$$

which couples gluon and quark degrees of freedom in the nucleon. The computed spin asymmetry for pion production [5] is proportional to a derivative of $T_F^{(V)}$, which enhances the cross section in the large-x_F region, where substantial effects are seen at moderate p_T [1]. The form of the leading-order calculation suggests that the twist-3 cross section will remain observable at RHIC energies, and predicts explicit dependences on kinematic variables that can be tested, perhaps with the Brahms detector [6].

References

[1] D.L. Adams et al., Phys. Lett. B261, 201 (1991); B264, 462 (1991); A. Bravar et al., Phys. Rev. Lett. 77, 2626 (1996).

[2] A.V. Efremov and O.V. Teryaev, Phys. Lett. 150B, 383 (1985); Yad. Fiz. 36, 950 (1982); 39, 1517, (1984) [Sov. J. Nucl. Phys. 36, 557 (1982); 39, 962 (1984)].

[3] J.W. Qiu and G. Sterman, Phys. Rev. Lett. 67, 2264 (1991); Nucl. Phys. B378, 52 (1992).

[4] J. Ralston and D.E. Soper, Nucl. Phys. B152, 109 (1979); R.L. Jaffe and X. Ji, Phys. Rev. Lett. 67, 552 (1991); Phys. Lett. B284, 137 (1992).

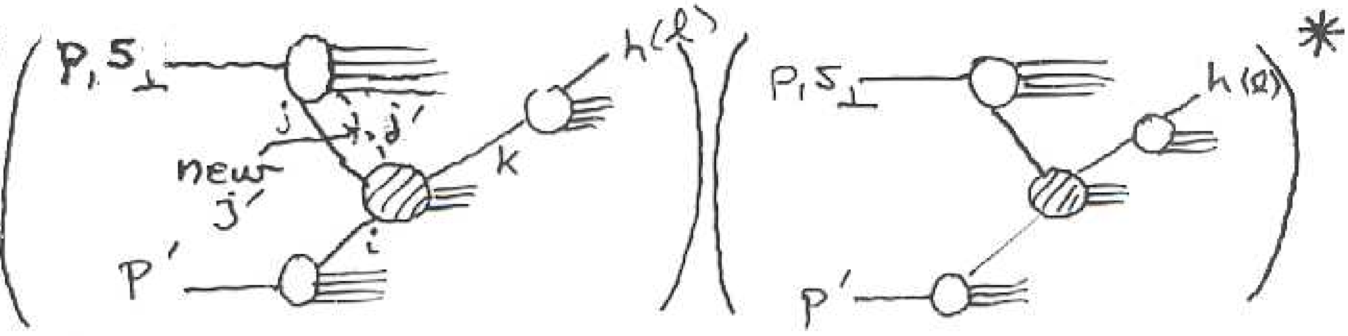
[5] J.W. Qiu and G. Sterman, in preparation.

[6] Flemming Videbaek, presentation at this workshop.

'MINIMAL APPROACH'

2. (Spin-Dependent) Factorization at $\mathcal{O}(1/Q)$ (what we need)

(1)



Interference $\rightarrow$ $\Delta\sigma(P, P', \ell, S_\perp)$

new $-\overset{j'}{-}--$ costs $1/Q \sim 1/\ell_\perp$

(2)

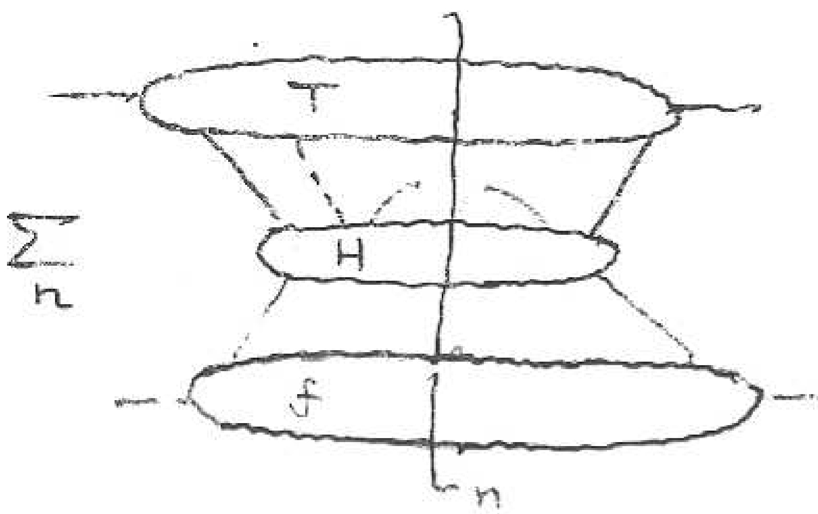
$$\omega \frac{d\Delta\sigma_\perp}{d^3 p} = \sum_{i(jj')k} \int \frac{dx_i}{x_i} f_{i/p}(x_i) \int \frac{dz}{z^2} D_{h/k}$$

$$* \int dx_j\, dx_{j'}\, T_{(jj')/p}(x_j, x_{j'})$$

$$* H_{i(jj')k}(x_i, x_j, x_{j'}, x_k, \ell)$$

$j, j' = q,\ D = i(\partial + igA),\ F$

(3)



work in DIS:
Vainshtein, Shuryak
Ellis, Furmanski
Petronzio
Jaffe, Soldate

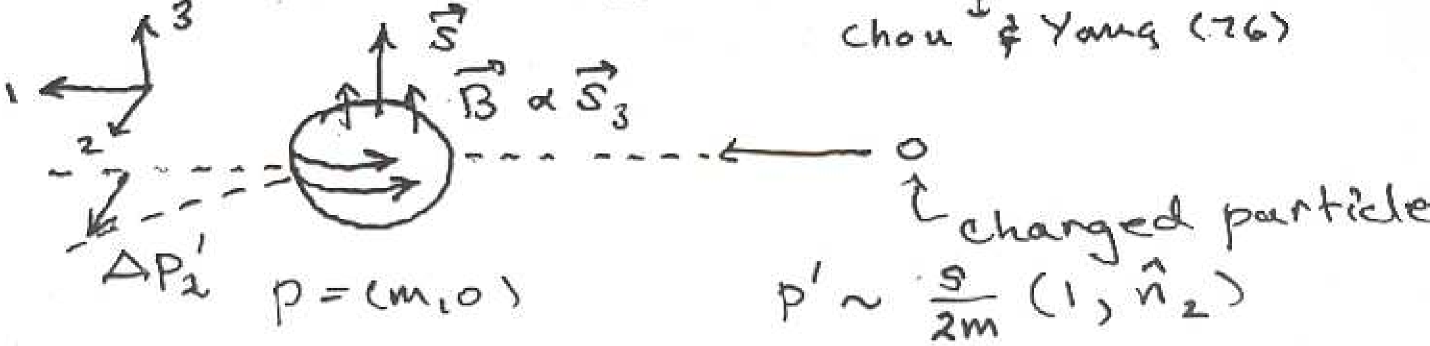
What are we looking at in $T_F^{(v)}$?
- Rotating Matter Currents?'

Classical (Abelian) Analog

rest frame of $(p, S_\perp)$

Liang & Meng (90)

Chou & Yang (76)



$$\dot{p}_2' = e(\vec{v}' \times \vec{B})_2$$

$$= -e v_1 B_3$$

$$= e v_1 F_{21}$$

cm frame $(m, \underline{0}) \to n$

$(1, \hat{n}_2) \to \bar{n}$

$$\dot{p}_2' = e n^\alpha F_{\alpha\rho} \epsilon^{\rho\nu\lambda\sigma} n_\nu \bar{n}_\lambda S_\sigma$$

$$\Delta p_i = \int dy \, \dot{p}_i$$

But recall $T_F^{(v)}$ a quantum correlation

$\Rightarrow$ new information on parton/parton correlations

We believe $\frac{dT_F^{(V)}}{dx}$ term dominates

(1) Because we expect

$$T_F^{(V)}(x,x) > T_D^{(V,A)}(x,0)$$

overlap of states that differ by soft gluon emission > 'soft quark' emission!

(2) Because if

$$T_F^{(V)}(x,x) \approx A(1-x)^N$$

$$\frac{d}{dx} T_F^{(V)}(x,x) = AN(1-x)^{N-1} \gg T_F^{(V)}$$

So: in more complicated processes it may make sense to only look at $\frac{d}{dx}$ terms for large x_F, x_T

But: $\frac{d}{dx} \leftrightarrow \frac{d}{dk_T} \leftrightarrow \langle \bar{\psi} F \psi \rangle$ $(x_F \to 1)$ 'soft'

or $\langle F F F \rangle$ $(x_F \lesssim 0)$? (10

3. Results

SPIN ASYMMETRY:

$$E_\ell \frac{d^3\Delta\sigma(\vec{s}_T)}{d^3\ell} = \frac{\alpha_s^2}{S}\sum_{a,c}\int_{z_{\min}}^1 \frac{dz}{z^2} D_{c\to\pi}(z)$$
$$\times \int_{x_{\min}}^1 \frac{dx}{x}\frac{1}{xS+U/z}\int \frac{dx'}{x'}\delta\left(x' - \frac{-xT/z}{xS+U/z}\right)$$
$$\times\sqrt{4\pi\alpha_s}\left(\frac{\epsilon^{\ell s_T n \bar{n}}}{z(-\hat{u})}\right)$$
$$\times\left[-x\frac{\partial}{\partial x}T_{F_a}^{(V)}(x,x)\right]\left[\Delta\hat{\sigma}_{ag\to c}G(x') + \Delta\hat{\sigma}_{aq\to c}\sum_q q(x')\right]$$

OUR FAVORITE MATRIX ELEMENT:

$$T_{F_a}^{(V)}(x,x) = \int \frac{dy^-}{4\pi} e^{ixP^+y^-}\langle P,\vec{s}_T|\bar{\psi}_a(0)\gamma_+\left[\int dy_2^-\, \epsilon^{s_T\sigma n\bar{n}} F_{\sigma+}(y_2^-)\right]\psi_a(y^-)|P,\vec{s}_T\rangle$$

COMPARE TO:

$$q_a(x) = \int \frac{dy^-}{4\pi} e^{ixP^+y^-}\langle P|\bar{\psi}_a(0)\gamma_+\psi_a(y^-)|P\rangle$$

MODEL:

$$T_{F_a}^{(V)}(x,x) \equiv \kappa_a\,\lambda\, q_a(x)$$

only for 'large' x !

$$\kappa_u = +1 \quad \text{and} \quad \frac{\kappa_u}{\kappa_d} = -1 \quad \text{(proton)}$$

viz A. Schafer et al PL B321, 121 (94)

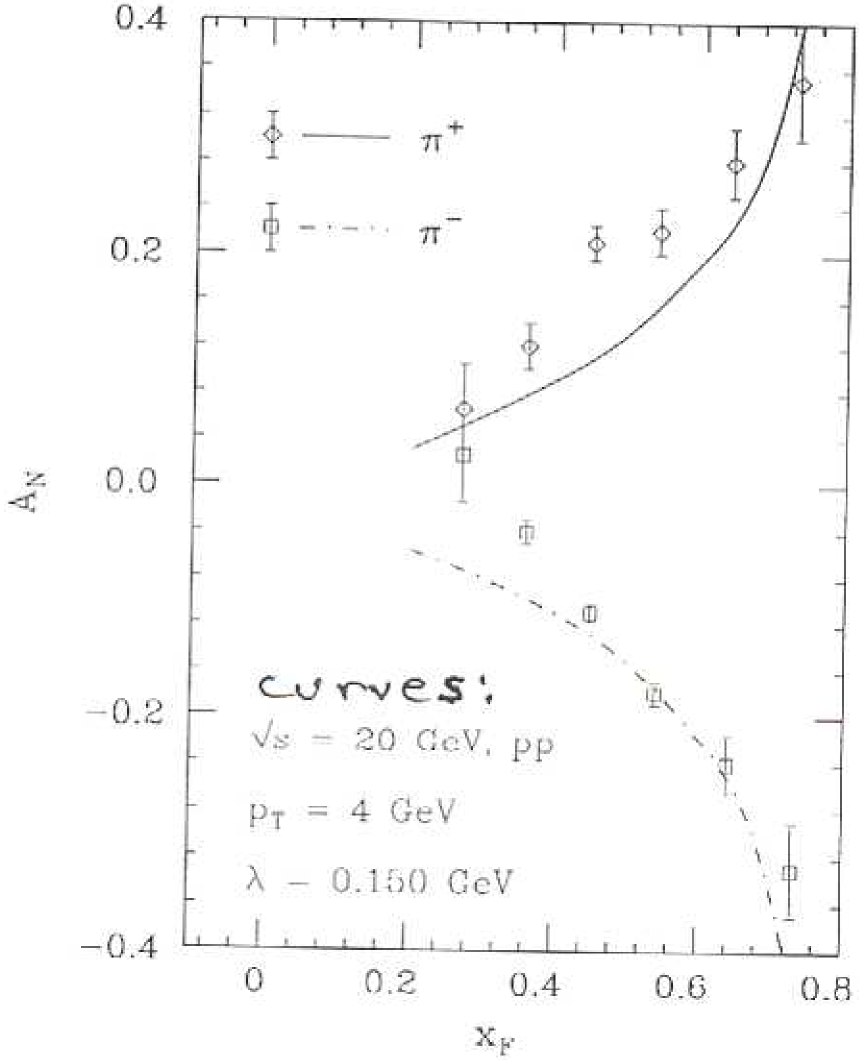
qg SHORT DISTANCE FUNCTION:

note relative size

$$\Delta\hat{\sigma}_{qg\to c} = \delta_{qc}\Big\{2\left(1-\frac{\hat{s}\hat{u}}{\hat{t}^2}\right)\left[\frac{9}{16}+\frac{1}{8}\left(1+\frac{\hat{u}}{\hat{t}}\right)\right]$$
$$+\frac{4}{9}\left(\frac{-\hat{u}}{\hat{s}}+\frac{\hat{s}}{-\hat{u}}\right)\left[\frac{63}{128}-\frac{1}{64}\left(1+\frac{\hat{u}}{\hat{t}}\right)\right]$$
$$+\left(\frac{\hat{s}}{\hat{t}}+\frac{\hat{u}}{\hat{t}}\right)\left[\frac{9}{16}+\frac{1}{8}\left(1+\frac{\hat{u}}{\hat{t}}\right)\right]$$
$$+\left[\frac{9}{32}\left(\frac{-\hat{u}}{\hat{s}}-\frac{\hat{s}}{-\hat{u}}\right)\right]+\left[\frac{9}{16}\left(\frac{\hat{s}}{\hat{t}}-\frac{\hat{u}}{\hat{t}}\right)\right]\Big\}$$

qq, $q\bar{q}$ SHORT DISTANCE FUNCTIONS:

$$\Delta\hat{\sigma}_{ab\to c} = \delta_{ac}\delta_{bq}\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right)\left[\frac{21}{64}+\frac{1}{8}\left(1+\frac{\hat{u}}{\hat{t}}\right)\right]$$
$$+\ \delta_{ac}\delta_{b\bar{q}}\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right)\left[-\frac{51}{64}+\frac{1}{8}\left(1+\frac{\hat{u}}{\hat{t}}\right)\right]$$
$$+\ \delta_{bc}\frac{4}{9}\left(\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)\left[\frac{21}{64}-\frac{51}{64}\left(1+\frac{\hat{u}}{\hat{t}}\right)\right]$$
$$+\ \delta_{ab}\delta_{bc}\frac{-8}{27}\left(\frac{\hat{s}^2}{\hat{u}\hat{t}}\right)\left[\frac{10}{8}+\frac{1}{8}\left(1+\frac{\hat{u}}{\hat{t}}\right)\right]$$
$$+\ \delta_{a\bar{b}}\frac{4}{9}\left(\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)\left[\frac{1}{8}-\frac{51}{64}\left(1+\frac{\hat{u}}{\hat{t}}\right)\right]$$



data at $\lesssim$ 1.5 GeV