Transversity Properties of Quarks and Hadrons in SIDIS and Drell-Yan

Leonard P. Gamberg* and Gary R. Goldstein†

*Division of Science, Penn State Berks, Reading, PA 19610, USA
†Department of Physics and Astronomy, Tufts University, Medford, MA 02155, USA

Abstract. We consider the leading twist T-odd contributions as the dominant source of the azimuthal and transverse single spin asymmetries in SIDIS and dilepton production in Drell-Yan Scattering. These asymmetries contain information on the distribution of quark transverse spin in (un)polarized protons. In the spectator framework we estimate these asymmetries at HERMES kinematics and at 50 GeV for the proposed experiments at GSI, where an anti-proton beam is ideal for studying the transversity properties of quarks due to the dominance of *valence* quark effects.

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One of the persistent challenges confronting the QCD parton model is to provide a theoretical basis for the experimentally significant azimuthal and transverse spin asymmetries that emerge in inclusive and semi-inclusive processes. Generally speaking, the spin dependent amplitudes for the scattering will contribute to non-zero transverse single spin asymmetries (SSA) if there are imaginary parts of bilinear products of those amplitudes that have overall helicity change. In perturbative QCD (PQCD), applicable to the hard scattering region, to obtain an imaginary contribution to quark and/or gluon scattering processes demands introducing higher order corrections to tree level processes. One approach incorporates the requisite phases through interference of tree level and one-loop contributions in PQCD in an attempt to explain up-down polarization asymmetry in Λ production [1]. On general grounds the helicity conservation property of massless QCD predicts that such contributions are small, going like $\alpha_s m/Q$, where α_s is the strong coupling, m represents a non-zero quark mass and Q represents the hard QCD scale [1, 2]. Such contributions have failed to account for the large SSA observed in Λ production [3].

However, considering the soft contributions to hadronic processes opens up the possibility that there are non-trivial transversity parton distributions that can contribute to transverse spin asymmetries [4]. For transverse SSA in SIDIS, transverse momentum must be acquired to lead to appropriate helicity changes at leading twist. In describing transverse asymmetries this is particularly relevant when the transverse momentum can arise from intrinsic quark momenta. Here the effects are associated with non-perturbative transverse momentum distribution functions [5] (TMD), where transverse SSAs indicate so called T-odd correlations between transverse spin and longitudinal and intrinsic quark transverse momentum. The T-odd distributions [6, 7] are of importance as they possess both transversity properties and the necessary phases to account for SSA and azimuthal asymmetries [8, 9]. Formally, these phases can be generated from the gauge invariant definitions of the T-odd quark distribution functions [10, 11, 12]. In contrast to the transverse SSAs generated from the interference of tree-level and one loop correction in PQCD, such effects go like $\alpha_s {<} k_\perp {>} / M$, where now M plays the role of the chiral symmetry breaking scale and $k_\perp$ is characteristic of quark intrinsic motion.

Here we consider the leading twist T-odd contributions as the dominant source of the $\cos 2\phi$ azimuthal asymmetry and $\sin(\phi \pm \phi_s)$ transverse SSAs in SIDIS [13] and azimuthal asymmetry ν in dilepton production in Drell-Yan Scattering [14]. Among other interesting properties, these asymmetries contain information on the distribution of quark transverse spin in an unpolarized proton, $h_1^\perp(x, k_\perp)$ [7]. In a parton-spectator framework we estimate these asymmetries at HERMES kinematics [15] and for Drell-Yan scattering at 50 GeV center of mass energy. The latter azimuthal asymmetry is interesting in light of proposed experiments at GSI, where an anti-proton beam will ideal for studying the transversity properties of quarks due to the dominance of *valence* quark effects [16].

The leading twist contributions to the factorized cross-section for a transversely polarized nucleon target in lepton-proton scattering are

$$\frac{d^6\sigma_{UT}^{\ell N^\uparrow \to \ell \pi X}}{dx_H dy dz_h d\phi_S d^2P_{h\perp}} = \frac{2\alpha^2}{Q^2 y} \Bigg\{ |S_T|(1-y)\sin(\phi_h + \phi_S) \sum_q e_q^2 \mathscr{F}\left[\frac{p_\perp \cdot \hat{h}}{M_h} h_1^q H_1^{\perp q}\right] + |S_T| \frac{\left(1+(1-y)^2\right)}{2} \sin(\phi_h - \phi_S) \sum_q e_q^2 \mathscr{F}\left[\frac{k_\perp \cdot \hat{h}}{M} f_{1T}^{\perp q} D_1^q\right]\Bigg\}, \tag{1}$$

where $\mathscr{F}$ is the convolution integral [7]. The twist two T-even and odd distribution and fragmentation functions appearing in Eq. (1) are projected from the correlation functions for the transverse momentum dependent distribution and fragmentation correlators, $\Phi(x, P)$ and $\Delta(p, P_h)$ respectively,

$$\Phi(x, p_\perp) = \frac{1}{2}\Big\{ f_1(x, p_\perp) \not{n}_+ + h_1^\perp(x, p_\perp) \frac{\sigma_{\mu\nu} p_\perp^\mu n_+^\nu}{M} + f_{1T}^\perp(x, p_\perp) \frac{\varepsilon_{\mu\nu\rho\sigma}\gamma^\mu n_+^\nu p_\perp^\rho S_T^\sigma}{M} \cdots \Big\}$$

$$\Delta(z, k_\perp) = \frac{1}{4}\Big\{ D_1(z, zk_\perp) \not{n}_- + H_1^\perp(z, zk_\perp) \frac{\sigma_{\mu\nu} k_\perp^\mu n_-^\nu}{M_h} + \cdots \Big\},$$

where for example $\int dp^- \mathrm{Tr}\left(\sigma^{\perp +}\gamma_5 \Phi\right) = \frac{2\varepsilon_{+-\perp j} p_{\perp j}}{M} h_1^\perp(x, p_\perp) \ldots$. We use the parton inspired quark-diquark spectator framework to model the quark-hadron interactions that enter the T-odd and even TMDs and fragmentation functions contributing to $\Phi(x, P)$ and $\Delta(z, P_h)$ [13]. Noting that parton intrinsic transverse momentum yields a natural regularization for the moments of these distributions, we incorporated a Gaussian from factor into our model. The resulting scalar diquark contribution is $h_1^\perp(x, p_\perp) = \mathscr{N} \alpha_s M \frac{(1-x)(m+xM)}{p_\perp^2 \Lambda(p_\perp^2)} \mathscr{R}(p_\perp^2; x)$ where $\mathscr{R}(p_\perp^2; x) = \exp^{-2b(p_\perp^2 - \Lambda(0))}\left(\Gamma(0, 2b\Lambda(0)) - \Gamma(0, 2b\Lambda(p_\perp^2))\right)$ is the regularization function. $\Lambda(k_\perp^2)$ is the spectral function and $\mathscr{N}$ is a normalization factor determined with respect to the unpolarized u-quark distribution, obtained from the zeroth moment of $f_1^{(u)}(x, p_\perp)$ normalized with respect to valence distributions. Our regulated expression of the Collins function is given by $H_1^\perp(z, k_\perp) = \mathscr{N}' \alpha_s \frac{1}{4z} \frac{(1-z)}{z} \frac{\mu}{\Lambda'(k_\perp^2)} \frac{M_\pi}{k_\perp^2} \mathscr{R}(z, k_\perp^2)$ where μ is

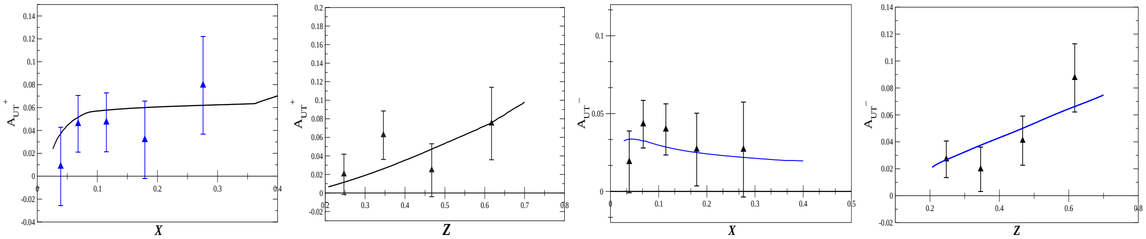

FIGURE 1. Left two Panel: The $\langle \sin(\phi+\phi_s)\rangle_{UT}$ asymmetry for π^+ production as a function of x and z compared to the HERMES data [15] Right two Panels: The $\langle \sin(\phi-\phi_S)\rangle_{UT}$ as a function of x and z.

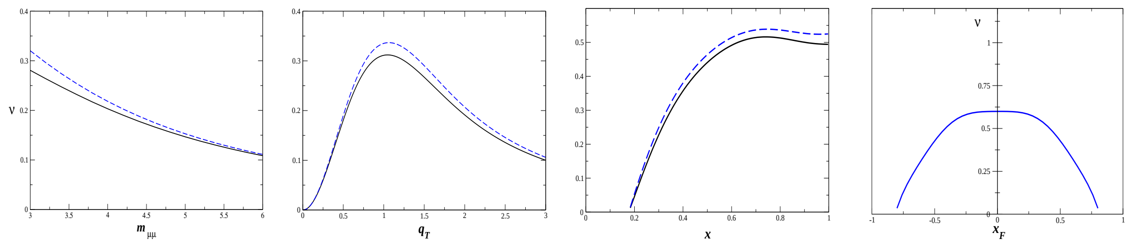

FIGURE 2. Left two Panels: ν plotted as a function of q_T and $q = m_{\mu\mu}$ for $s = 50$ GeV^2, x in the range $0.2-1.0$. Right two panels: ν plotted as a function of x and x_F for $s = 50$ GeV^2 q_T ranging from 3 to 6 GeV/c and q from 0 to 3 GeV/c.

the quark spectator mass and $\mathcal{N}'$ is determined from the normalization on the unpolarized fragmentation function $D_1(z)$. The Collins and Sivers weighted asymmetries are projected from the differential cross sections, Eq. (1)

$$\langle \frac{P_{h\perp}}{M_\pi}\sin(\phi+\phi_s)\rangle_{UT} = \frac{\int d\phi_s d^2P_{h\perp}\frac{P_{h\perp}}{M_\pi}\sin(\phi+\phi_s)\left(d\sigma^\uparrow - d\sigma^\downarrow\right)}{\int d\phi_s \int d^2P_{h\perp}\left(d\sigma^\uparrow + d\sigma^\downarrow\right)} = \frac{|S_T|2(1-y)\sum_q e_q^2 h_1(x) zH_1^{\perp(1)}(z)}{(1+(1-y)^2)\sum_q e_q^2 f_1(x)D_1(z)}$$

and $\langle \frac{|P_{h\perp}|}{M}\sin(\phi-\phi_S)\rangle_{UT} = |S_T|\frac{(1+(1-y)^2)\sum_q e_q^2 f_{1T}^{\perp(1)}(x) zD_1^q(z)}{(1+(1-y)^2)\sum_q e_q^2 f_1(x)D_1(z)}$. We have re-analyzed these asymmetries including both the scalar and vector diquark contributions to the TMDs for the central values of our parameter set, and compared the transverse SSAs to the the HERMES data [15] for π^+ production in Fig. 1. The unweighted asymmetries are approximated as $A_{UT}^{\sin(\phi+\phi_s)} \approx \frac{M_\pi}{\langle P_{h\perp}\rangle}\langle \frac{P_{h\perp}}{M_\pi}\sin(\phi+\phi_s)\rangle$ and $A_{UT}^{\sin(\phi-\phi_s)} \approx \frac{M}{\langle P_{h\perp}\rangle}\langle \frac{P_{h\perp}}{M}\sin(\phi\pm\phi_s)\rangle$. These results agree to within the errors displayed.

An unpolarized double T-odd azimuthal asymmetry enters the Drell-Yan process [17]. For the Drell-Yan process the angular dependence [18] can be expressed as

$$\frac{dN}{d\Omega} \equiv = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1+\lambda\cos^2\theta + \mu\sin^2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right), \quad (2)$$

where $\frac{dN}{d\Omega} \equiv \left(\frac{d\sigma}{dQ^2dydq_T^2}\right)^{-1}\frac{d\sigma}{dQ^2dydq_T^2d\Omega}$. The solid angle Ω refers to the lepton pair orientation in the pair rest frame relative to the boost direction, and λ, μ, ν are functions that depend on $x, m_{\mu\mu}^2, q_T$, the fraction of quark momentum in the hadron, the invariant mass of the produced lepton pair, and the transverse momentum of the dimuon pair. All of the asymmetry functions, μ, λ and ν, have parton model contributions which at next to leading order predict $1-\lambda-2\nu=0$, the so called Lam-Tung relation [19]. Experimental measurements of $\pi p \to \mu^+\mu^- X$ discovered unexpectedly large values of these asymmetries [20] compared to parton-model expectations resulting in a serious violation of this relation. It has been suggested [17] that there is a dominant leading twist contribution to ν coming from the T-odd transversity distributions $h_1^\perp(x,k_\perp)$ for both hadrons which dominates in the kinematic range, $q_T \ll Q$. The $\cos 2\phi$ azimuthal asymmetry in unpolarized $p\bar{p} \to \mu^+\mu^- X$ involves the convolution of the leading twist T-odd function, $h_1^\perp$ $\nu_2 = \frac{\sum_a e_a^2 \mathscr{F}\left[w_2 h_1^\perp(x,k_\perp)\bar{h}_1^\perp(\bar{x},p_\perp)/(M_1 M_2)\right]}{\sum_a e_a^2 \mathscr{F}\left[f_1(x,k_\perp)\bar{f}_1(\bar{x},p_\perp)\right]}$ where $w_2 = (2\hat{h}\cdot k_\perp \cdot \hat{h}\cdot p_\perp - p_\perp \cdot k_\perp)$ is the weight in the convolution integral, $\mathscr{F}$. In addition it is known that there is a non-leading T-even contribution to the $\cos 2\phi$ asymmetry[18] $\nu_4 = \frac{\frac{1}{Q^2}\sum_a e_a^2 \mathscr{F}\left[w_4 f_1(x,k_\perp)\bar{f}_1(\bar{x},p_\perp)\right]}{\sum_a e_a^2 \mathscr{F}\left(f_1(x,k_\perp)\bar{f}_1(\bar{x},p_\perp)\right)}$, where $w_4 = 2(\hat{h}\cdot(k_\perp - p_\perp))^2 - (k_\perp - p_\perp)^2$ and $\hat{h} = q_T/Q_T$. Fig. 2 shows that the $\cos 2\phi$ azimuthal asymmetry ν is not small at center of mass energies of 50 GeV^2. However the T-odd portion dominates with an additional $3-5\%$ from the sub-leading T-even piece. Thus, aside from the competing T-even effect, the experimental observation of a strong x-dependence would indicate the presence of T-odd structures in *unpolarized* Drell-Yan scattering, implying that novel transversity properties of the nucleon can be accessed *without invoking beam or target polarization*.

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