TRANSVERSE QUARK SPIN EFFECTS IN SIDIS AND UNPOLARIZED DRELL YAN

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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 at low transverse momentum scales. In the spectator framework we estimate these asymmetries at HERMES and CLAS-12 JLAB kinematics as well as at 50 GeV for proposed experiments at GSI.

One of the persistent challenges confronting the QCD parton model is to provide a theoretical basis for the significant azimuthal and transverse spin asymmetries that emerge in inclusive and semi-inclusive processes. Spin dependent amplitudes for the scattering contribute to non-zero transverse single spin asymmetries (TSSAs) if there are imaginary parts of bilinear products of those amplitudes that have overall helicity change. To obtain an imaginary contribution to partonic scattering processes in perturbative QCD (PQCD) for transverse momentum $\boldsymbol{P}_T \gg \Lambda_{\rm qcd}$ demands introducing higher order corrections to tree level processes. On general grounds QCD predicts that such contributions are small, going like $\alpha_s m/Q$, where α_s is the strong coupling, m represents a quark mass and Q represents the hard QCD scale[1]. Historically such contributions fall short in accounting for large observed TSSAs[2]. However, considering the soft contributions to hadronic processes opens up the possibility that there are non-trivial transversity parton distributions that contribute to transverse spin asymmetries[3]. In describing transverse spin asymmetries this is particularly relevant when the transverse momentum $\boldsymbol{P}_T \sim \boldsymbol{k}_\perp$, where $\boldsymbol{k}_\perp$ is intrinsic quark momenta. Here the effects are associated with non-perturbative transverse momentum distribution functions(TMDs)[4], where TSSAs indicate so called T-odd correlations between transverse spin and intrinsic quark transverse momentum. These distributions[5,6] possess both transversity properties and the necessary phases to account for TSSA and azimuthal asymmetries[7,8]. Formally, phases are generated from the gauge invariant definitions of the T-odd quark distribution functions[9,10,11]. In contrast to PQCD, such effects go like $\alpha_s k_\perp/M$, where now M plays the role of the chiral symmetry breaking scale.

Here, we consider the leading twist T-odd contributions as the dominant source of the $\sin(\phi\pm\phi_s)$ TSSAs and $\cos 2\phi$ azimuthal asymmetry in SIDIS[12]. They enter at leading twist for lepton-nucleon scattering

$$\frac{d^6\sigma^{\ell N\to\ell\pi X}}{dxdydzd\phi_S d^2\boldsymbol{P}_{h\perp}} \sim \Big\{ |\boldsymbol{S}_T|(1-y)\sin(\phi_h+\phi_S)\sum_q e_q^2\,\mathcal{F}\left[\frac{\boldsymbol{p}_\perp\cdot\hat{\boldsymbol{h}}}{M_h}\,h_1^q H_1^{\perp q}\right]$$
$$+|\boldsymbol{S}_T|\frac{(1+(1-y)^2)}{2}\sin(\phi_h-\phi_S)\sum_q e_q^2\,\mathcal{F}\left[\frac{\boldsymbol{k}_\perp\cdot\hat{\boldsymbol{h}}}{M}\,f_{1T}^{\perp q}D_1^q\right]$$
$$+(1-y)\cos 2\phi_h\,\sum_q e_q^2\,\mathcal{F}\left[\frac{2(\boldsymbol{k}_\perp\cdot\hat{\boldsymbol{h}})(\boldsymbol{p}_\perp\cdot\hat{\boldsymbol{h}})-\boldsymbol{k}_\perp\cdot\boldsymbol{p}_\perp}{MM_h}\,h_1^{\perp q}H_1^{\perp q}\right]\Big\}, \quad (1)$$

where $\mathcal{F}$ is the convolution integral[6]. The twist two T-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 $\Delta(z,P_h)$[6]. We use the parton inspired spectator framework to model the quark-hadron interactions that enter the T-odd and even TMDs and fragmentation functions[12]. Noting that parton intrinsic transverse momentum yields a natural regularization for the moments of these distributions, we incorporate a Gaussian from factor into our model. The resulting scalar diquark contribution to the Boer Mulders function is equal to the Sivers function[11], $h_1^\perp(x,p_\perp)=f_{1T}^\perp(x,p_\perp)=\mathcal{N}\alpha_s M\frac{(1-x)(m+xM)}{p_\perp^2\Lambda(p_\perp^2)}\mathcal{R}(p_\perp^2;x)$, where $\mathcal{R}(p_\perp^2;x)$ is the regularization function. $\Lambda(k_\perp^2)$ is a function of $p_\perp, x$ and masses, and $\mathcal{N}$ is a normalization factor determined with respect to the unpolarized u-quark distribution, $f_1^{(u)}(x,p_\perp)$. Our regulated expression of the Collins function[12] is given by $H_1^\perp(z,k_\perp)=\mathcal{N}'\alpha_s\frac{(1-z)}{4z^2}\frac{M_\pi}{k_\perp^2}\frac{\mu-m(1-z)}{\Lambda'(k_\perp^2)}\mathcal{R}(\boldsymbol{k}_\perp^2;z)$ where μ is 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 cross sections, Eq. (1)

$$A_{UT}^{\sin(\phi+\phi_s)}\sim\frac{\sum_q e_q^2 h_1(x)zH_1^{\perp(1)}(z)}{\sum_q e_q^2 f_1(x)D_1(z)},\;A_{UT}^{\sin(\phi-\phi_s)}\sim\frac{\sum_q e_q^2 f_{1T}^{\perp(1)}(x)zD_1^q(z)}{\sum_q e_q^2 f_1(x)D_1(z)}.$$

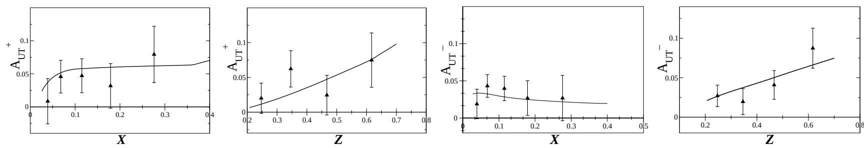

Figure 1. The Collins and Sivers TSSAs $\langle\sin(\phi \pm \phi_s)\rangle_{UT}$ for π^+ production as a function of x and z compared to the HERMES data.

We have re-analyzed these asymmetries[13] including both the scalar and vector diquark contributions to the TMDs for the central values of our parameter set, and compared the TSSAs to the the HERMES data[14] for π^+ production in Fig. 1. These results agree to within the errors displayed.

For Drell-Yan processes the angular dependence[15] is expressed as

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \equiv \frac{3}{4\pi}\frac{1}{\lambda+3}\Big(1+\lambda\cos^2\theta+\mu\sin^2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\Big). \quad (2)$$

The solid angle Ω refers to the lepton pair orientation in the rest frame relative to the boost direction. λ, μ, ν depend on $x, m^2_{\mu\mu}, \boldsymbol{q}_T$, the hadronic fraction of quark momentum, the lepton pair invariant mass, and the transverse momentum of the dimuon pair. These asymmetry functions, have parton model contributions which at next to leading order predict $1-\lambda-2\nu=0$, the so called Lam-Tung relation[17]. Experimental measurements of $\pi^- p \to \mu^+\mu^- X$[18] discovered a serious violation of this relation. It has been suggested by Boer[19] that there is a dominant leading twist contribution to ν coming from the Boer Mulders distribution $h_1^\perp(x, k_\perp)$ for both hadrons when $\boldsymbol{q_T} < Q$ for moderate Q^2. The $\cos 2\phi$ azimuthal asymmetry in unpolarized $p\bar{p} \to \mu^+\mu^- X$ involves the convolution of the leading twist T-odd functions, $\nu_2 \sim \sum_a e_a^2 \mathcal{F}\left[w_2\, h_1^\perp(x,k_\perp)\bar{h}_1^\perp(\bar{x},p_\perp)/(M_1 M_2)\right]$ where w_2 is the weight in the convolution integral, $\mathcal{F}$. In addition it is known that there is a non-leading T-even contribution to the $\cos 2\phi$ asymmetry[15] $\nu_4 \sim \frac{1}{Q^2}\sum_a e_a^2 \mathcal{F}\left[w_4\, f_1(x,k_\perp)\bar{f}_1(\bar{x},p_\perp)\right]$. Fig. 2 shows that the $\cos 2\phi$ azimuthal asymmetry ν is not small[20] at center of mass energies of 50 GeV^2. While the T-odd portion dominates with $q_T \leq$3 GeV/c and 3 GeV/c $\leq q \leq$ 6 GeV/c, taking into account $\boldsymbol{q}_T/Q$ kinematic corrections results in an additional $5-8\%$ from the sub-leading T-even piece. Additionally we display the SIDIS $\cos 2\phi$ azimuthal asymmetry as a function of $\boldsymbol{P}_{hT}$ for $\pi^\pm$ production assuming $H_{1\perp}^{\text{fav}} = -H_{1\perp}^{\text{disfav}}$ at CLAS-12 GeV kinematics[13], where $\boldsymbol{P}_{hT} < Q$. Thus, aside from the competing T-even effect, the experimental observation of *e.g.* strong dependence on transverse momentum would indicate the presence of T-odd structures in *unpolarized* SIDIS and Drell-Yan

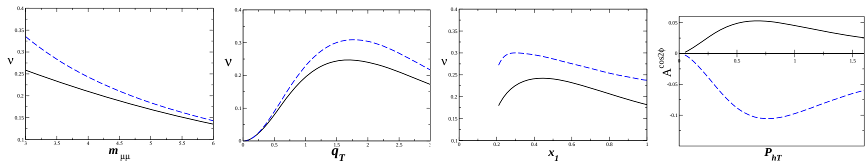

Figure 2. Left to right: ν plotted as a function of $m_{\mu\mu}$, q_T and x_1 for $s = 50$ GeV^2: x range $0.2 - 1.0$, q_T range: $3 - 6$GeV$/c$ and q range: $0 - 3$GeV$/c$. $\cos 2\phi$ SIDIS asymmetry versus P_T for CLAS-12 kinematics.

scattering, implying that novel transversity properties of the nucleon can be accessed *without invoking beam or target polarization*.

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