BRIEF REPORTS

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Hard-scattering scaling laws for single-spin production asymmetries

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The extraction of a scaling law of the form $[(p_T^2+\mu^2)/\mu p_T]A_N \cong g(x_T)$ (where $x_T=2p_T/\sqrt{s}$) from data on a single-spin production asymmetry such as $A_N d\sigma(pp_\uparrow \to \pi^0 X)$ at large transverse momentum can be used to argue for an underlying "hard-scattering" mechanism. Data from the upcoming Fermilab polarized beam experiment (E-704) can be used to test the scaling hypothesis.

In a parity-conserving theory there can exist a nontrivial single-spin production asymmetry

$$A_N(pp_\uparrow \to \pi X) = \frac{d\sigma(pp_\uparrow \to \pi X) - d\sigma(pp_\downarrow \to \pi X)}{d\sigma(pp_\uparrow \to \pi X) + d\sigma(pp_\downarrow \to \pi X)} ,$$

where the polarized proton's spin is transverse to its direction of motion and the momentum of the produced pion is normal to both the proton spin and momentum. For large-transverse-momentum production, it is interesting to test whether such a single-spin production asymmetries as $A_N d\sigma(pp_\uparrow \to \pi^0 X)$ or $A_N d\sigma(pp_\uparrow \to \text{jet } X)$ can be understood within the overall context of the QCD hard-scattering model. Some theoretical studies[1] have been used to claim that such single-spin observables must strictly vanish in the hard-scattering regime because of quark-helicity conservation and, hence, that any nonvanishing asymmetry is to be taken as an indication that the data are not yet in a kinematic region where QCD perturbation theory can be considered valid.

It is possible to refute this argument. There exists a body of theoretical work[2,3] that has questioned the hypothesis that the vanishing of single-spin asymmetries is necessary in the hard-scattering regime by pointing out that "hadronic" masses rather than "current-quark" masses can enter into the calculation of such observables in QCD. In order to demonstrate the underlying principle, in a recent paper[2] I showed that when one accepts the possibility of asymmetries in the intrinsic-k_T distribution of constituents within a polarized proton, there exists a well-understood kinematic, "trigger-bias," effect in the formulation of the QCD-based hard-scattering model that can lead to significant single-spin production symmetries at large transverse momentum. This simple approach provides a hypothetical framework for understanding such observables as recognizable "higher-twist" components of the basic theory. In fact, the model advocated in Ref. 2 can be considered an extremely naive manifestation of the general theoretical picture in that the intrinsic-k_T distribution that gives the asymmetry is controlled by a hadronic mass scale and need not vanish as $m_q \to 0$.

However, it would be nice to bypass specific theoretical models and to formulate an explicitly experimental test for the presence of hard scattering. One useful criterion for defining the kinematic regime where hard-scattering dynamics are appropriate involves the application of scaling laws.[4] The basic assumption for the formulation of scaling laws is that the separation of hard-scattering and soft dynamics can be done in a manner only weakly dependent on the choice of factorization scale. When hard-scattering cross sections are "factored out" the remainder must depend only on scale-invariant kinematic variables. When this is done in the familiar example of deep-inelastic lepton scattering, the effects of scaling violations can be calculated in QCD perturbation theory and give rise to logarithmic evolution of parton densities. With similar assumptions, the presence of a pointlike hard-scattering mechanism responsible for the large-transverse-momentum production of a hadron can be signaled by a scaling law of the form[4]

$$\frac{E\,d\sigma}{d^3p}(pp \to \pi^0 X) \cong \left[\frac{\mu}{p_T}\right]^4 f(x_T,\mu^2) , \qquad (1)$$

where $x_T=2p_T/\sqrt{s}$.

For an observable such as A_N, the type of scaling law expected from hard scattering can be deduced from general kinematic constraints. However, it is easier to illustrate how the form arises. In Ref. 2, the proposal for the hard-scattering component of the single-spin asymmetry is written

$$A_N\left[E\frac{d^3\sigma}{d^3p}(pp_\uparrow\to mX\right]$$
$$\simeq\sum_{ab\to cd}\int d^2\mathbf{k}_T^a dx_a\int d^2\mathbf{k}_T^b dx_b\int d^2k_{Tc}\frac{dx_c}{x_c^2}\Delta^N G_{a/p_\uparrow}(x_a,k_{TN}^a,k_{TS}^a;\mu^2)G_{b/p}(x_b,k_T^{b2};\mu^2)D_{m/c}(x_c,k_T^{c2};\mu^2)$$
$$\times\left\{\tilde{s}\frac{d\sigma}{d\tilde{t}}(ab\to cd)\delta(\tilde{s}+\tilde{t}+\tilde{u})\left[1+O\left[\frac{\alpha_s}{\pi}\right]\right]\right\}; \quad (2)$$

where $\Delta^N G_{a/p_\uparrow}(x,k_{TN},k_{TS};\mu^2)$ is the transverse-momentum asymmetry in the parton density of the transversely polarized proton. The δ function in (2) enforces 2-2 kinematic constraints and transmits information from the intrinsic asymmetry, $\Delta^N G_{a/p_\uparrow}$. out to large-transverse momentum. After integration over the intrinsic-transverse momenta, this expression can be cast in the form

$$A_N\left[\frac{d\sigma}{dy\,dp_T}(pp_\uparrow\to mX)\right]\cong\sum_{ab\to cd}\int dx_a dx_b\Delta^N G_{a/p_\uparrow}(x_a;\mu^2)G_{b/p}(x_b;\mu^2)\left[A_N\frac{d\hat{\sigma}}{dt\,dp_T}(ab\to mX)\right]. \quad (3)$$

Except for the "kinematic" origin of the underlying asymmetry, the structure of (3) is similar to that extracted from other incarnations of the hard-scattering model. Writing the analogous expression for the spin-averaged inclusive cross section and taking a ratio allows us to formulate a "scaling" form for the asymmetry

$$A_N|_{y=0}\cong a(p_T,\mu)g(x_T,\mu), \quad (4)$$

which is insensitive to the exact choice of factorization scale μ. The behavior of $a(p_T,\mu)$ can be roughly deduced from (2) since the hard-scattering function must vanish at $p_T=0$ and must behave as approximately $1/p_T$ at large p_T. A first guess at $a(p_t)$ might therefore be

$$a(p_T,\mu)=\frac{\mu p_T}{p_T^2+\mu^2}, \quad (5)$$

where μ is some hadronic mass scale with $m_q \ll \mu \ll p_T$. As shown in Ref. 2, this form can also be obtained by integrating the regularized cross sections over angle. The function $g(x_T,\mu)$ contains the information of the soft-coherent dynamics. At present, we do not have a theory for $g(x_T,\mu)$. In the model of Ref. 2 we can see that the distribution $\Delta^N G_{a/p_\uparrow}(x_a,k_{TN}^a,k_{TS}^a;\mu^2)$, which generates $g(x_T,\mu)$, should vanish at $x_a=0$. This leads to $g(0,\mu)=0$. In addition, the sum-rule constraint[2] for transverse-momentum conservation

$$\sum_a\int dx\,\Delta^N G_{a/p_\uparrow}(x,k_{TN},k_{TS};\mu^2)=0 \quad (6)$$

strongly suggests the possible existence of other zeros in $g(x_T,\mu)$. However, the ability to predict $g(x_T,\mu)$ is not a general feature of hard-scattering models.

In the absence of a full theory, we can attempt to extract the behavior of $g(x_T,\mu)$ directly from experimental data. Using the data on $A_N(hp_\uparrow\to\pi^0X)$ from Refs. 5 and 6, we plot

$$\left[\frac{p_T^2+\mu^2}{\mu p_T}\right]A_N\cong g(x_T,\mu) \quad (7)$$

for $\mu^2=0.5\ \mathrm{GeV}^2\cong m_\rho^2$. Within the quoted experimental errors, the data are consistent with the scaling hypothesis. However, this comparison is not a stringent test of scaling since the c.m. energies of the two experiments differ only by a factor of 1.28. A more interesting test would be to use these data and the scaling form (4) to predict the results of the asymmetry $A_N d\sigma(p_\uparrow p\to\pi^0X)$ for the Fermilab polarized-beam experiment at $\sqrt{s}=20$ GeV.[7] For example, the data in Fig. 1 suggest a zero in $g(x_T)$ at about $x_T=0.35$ followed by a steep rise to a plateau at $x_T=0.55-0.60$. At $\sqrt{s}=20$, this structure would imply a zero for A_N at $p_T\cong3.5$ GeV/c with a peak at $p_T=5.5-6.0$ GeV/c. Including the Fermilab data in the comparison should provide important insight since it would be hard to imagine a mechanism that did not involve hard scattering and that would give such structure for A_N in the E-704 p_T regime.

It should be emphasized that establishing the validity of a scaling law of the form (3) provides strong support

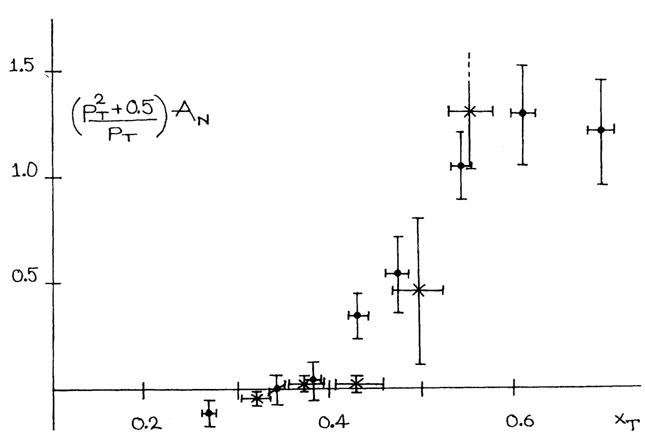

FIG. 1. Data from Ref. 5 (⋇) and Ref. 6 (⫯) on $A_N(p_T^2+0.5)/p_T$ plotted against x_T order to test the scaling law (4).

for the existence of some underlying component of hard-scattering without guaranteeing that the full mechanism can be understood in a fundamental theory. For example, the constituent counting-rule prediction of an approximate dipole form for the proton form factor seems to be observed in the data even though there is considerable controversy over whether the data are in a region where perturbative QCD applies.[8] Nonetheless, the absence of a well-formed theory makes an experimental test of scaling very interesting. For single-spin asymmetries, it seems particularly important to confront the widely disseminated idea that all such observable should strictly vanish at p_T values appropriate to hard scattering. Once there is clear evidence in the data for hard processes, we can begin to refine our theoretical ideas. Of course, there will aways be a question of what constitutes the asymptotic regime. In this context, it should be noted that in Ref. 2 I did *not* take seriously the idea that the data from Ref. 5 and 6 were in the large-p_T regime, and, hence, did not take seriously the idea of a scaling test involving these data sets. The curves shown there to illustrate the model are not consistent with $g(0,\mu)=0$ and can be misleading.

It should be possible to test the scaling hypothesis with data from the Fermilab E-704 experiment alone by comparing data sets from different laboratory energies. Since data from the same experiment on two-spin asymmetries will ultimately be used to extract information concerning parton spin densities,[9] it is extremely important to seek assurance that hard scattering is present.

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