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Quark flavor tagging in polarized hadronic processes

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We describe a general approach to quark flavor tagging in polarized hadronic processes, with particular emphasis on semi-inclusive deep inelastic scattering. A formalism is introduced that allows one to relate chosen quark flavor polarizations to an arbitrary combination of final-state hadron spin asymmetries. Within the context of the presented formalism, we quantify the sensitivity of various semi-inclusive hadron asymmetries to the light quark flavors. We show that *unpolarized* Λ's may allow one to measure strange quark and antiquark polarizations independently. We also highlight several applications of our formalism, particularly to measurements intended to probe further the spin structure of the nucleon. [S0556-2821(98)50221-4]

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I. INTRODUCTION

The interpretation of hard hadronic processes in terms of partonic (quark and gluon) degrees of freedom forms a vital component of modern research in particle physics. In particular, the tagging of parton quantum numbers, such as flavor and charge, using appropriately chosen final states allows important tests of both QCD and electroweak dynamics. In the remainder of this paper, we will focus primarily on the leptoproduction of hadrons in deep inelastic scattering (DIS), $\ell N \rightarrow \ell' hX$, where both initial states are polarized. Such measurements continue to provide important information on the spin structure of the nucleon [1]. However, the conceptual foundations of our approach and the formalism that we introduce pertain to any hard hadronic process, and other applications are mentioned in Sec. IV.

The spin structure of the nucleon has received much attention in the past decade [1]. The experimental focus until rather recently has been on the leading twist structure function $g_1(x,Q^2)$, which is roughly proportional to the inclusive spin asymmetry on a longitudinally polarized target. However, processes where at least one hadron is detected in the final state offer several distinct advantages over the inclusive process alone [2–5]. In particular, semi-inclusive reactions provide a direct probe of the flavor dependence of quark observables, allowing more stringent tests of hadron structure. Perhaps more importantly, semi-inclusive processes allow one to separate [4,5] contributions with definite charge conjugation symmetry. This is particularly interesting since charge-odd quantities are free of the axial anomaly. It has been recently suggested [6] that a comparison of the charge conjugation even and odd parts of parton helicity and transversity distributions may yield new information on the polarized gluon contribution to the nucleon spin.

Given this importance of semi-inclusive measurements in hard hadronic processes, it is useful to have a formalism that is independent of model assumptions. In Sec. III, we introduce a general method to extract chosen polarized quark distributions from an arbitrary combination of final state asymmetries. This new approach is particularly useful in light of the latest generation of existing [HERMES, Spin Muon Collaboration (SMC), TJNAF] and forthcoming [COMPASS, ELFE, HERA-$\vec{p}$, BNL Relativistic Heavy Ion Collider (RHIC) Spin] experimental efforts, which allow identification of a large number of final state hadrons. Within the framework of the presented formalism, we quantify the sensitivity, as a function of kinematics, of various hadrons to the light quark flavors.

II. GENERAL CONSIDERATIONS

Traditionally, quark flavor tagging has been applied almost exclusively to the current fragmentation region in deep inelastic processes. Since a separation between the current and target regions is usually regarded as a necessary criterion for such measurements, one imposes kinematic cuts in order to try to exclude the target region. Our point is that such a separation is not possible, even in principle, within a coherent and complete description of hadronic final states.[1] In perturbation theory, this follows from the existence of collinear singularities with respect to initial state partons that generate a contribution to the target fragmentation region [7]. We further argue that, generally speaking, there is no *a priori* reason to minimize the effects of target fragmentation. Indeed, it has been shown [7] that, independent of a transverse momentum cutoff, all collinear singularities for sufficiently hard hadrons can be absorbed into so-called fracture functions [8] $M^h_{i,N}(x,x_F,Q^2)$, which give the joint probability of "finding" within the target N a parton i and hadron h. Measurements sensitive to target fragmentation offer complementary information on the nucleon state [9] and additional insights into a unified view [10] of hadronic reactions.

Quark flavor tagging is based on the idea of local parton-hadron duality (LPHD) [11], where it is assumed that the flow of quantum numbers at the hadron level tends to follow the flow established at the parton level. At leading order in

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[1] Sophisticated hadronization models, such as the string and cluster models, reflect this fact.

perturbation theory (for infrared safe or factorizable parton quantities), this has the practical consequence that the parton-hadron correspondence is essentially one-to-one. Since quarks and gluons are not asymptotic states (due to confinement), it would be a mistake to conclude that we can ever measure, in effect, a primary parton, instead of merely an event property that is *correlated* with the primary parton. Within a complete description of hadronic processes, valid beyond the leading order, the relevant issue is the degree of correlation between the final state topology and the quantum numbers of the primary partons.

It is therefore instructive to discuss briefly the nature of parton-hadron correlations. Inclusive hadron distributions in all hadronic processes, regardless of whether the collisions are hard or soft, are characterized by projectile fragmentation regions separated by a central region [12]. The key feature of the central region is that it is essentially independent of both projectiles and hence universal for all hadronic processes (at fixed invariant mass W). This has been confirmed in hadron-hadron collisions [13], and indeed, hadron spectra in the central region are found to be very similar [14] in pp, $p\bar{p}$, photoproduction, and low-x DIS processes. These generic features of hadronic final states have been recognized [15,12] a long time ago to be a consequence of Lorentz invariance and short range correlations in rapidity.

Using an approach based on short range rapidity correlations and LPHD, we have calculated [6] the correlations of light hadrons with respect to the current quark and target remnant. Within our discussion, it is important to distinguish between forward ($x_F>0$) and backward ($x_F<0$) regions, which are *defined* strictly by kinematics, from the current, target, and central fragmentation regions, which are never distinct, but represent varying degrees of correlation with the quark and remnant. As the correlations depend strongly on rapidity differences, our definition of the fragmentation regions coincides with their classification, within perturbative QCD, in terms of collinear and soft divergences. This suggests that it is favorable to use hadronic variables such as x_F or rapidity over the usual energy fraction $z=E_h/E_\gamma$, since the latter variable cannot distinguish between the central and target regions (both dominate at low z).

In our calculations, we find that at small $|x_F|<0.1-0.2$ and *fixed* Q^2, both the current and target correlations decrease as W increases.[2] This implies that most of the increase in hadron production with increasing W occurs in the central region, a result well known from hadronic phenomenology. Indeed, in DIS at *constant* Q^2, the charged pion fragmentation functions $D^\pi(x_F,W)$ rise linearly with $\ln W$ at small $|x_F|<0.1$, but remain constant at larger values of $|x_F|$, both in the forward and backward regions [19]. This is an important result, because it illustrates that independent of the target remnant, there are kinematical effects in the forward region that cannot be described by fragmentation functions depending on z and Q^2 alone, as is usually assumed. For increasing values of W, while the current and target regions become better separated kinematically, the fraction of hadrons that are strongly correlated with the current quark decreases (roughly as 1/ln W). Even in the central region, however, the correlation between an arbitrary final state and the flavor of the current quark remains significant due to the finite number of accessible flavors. In the next section, we introduce a new formalism that allows one to quantify the above correlations and to relate chosen hadron-level asymmetries to the polarization of partons involved in the hard scattering process.

[2]Several quantitative examples were given in Ref. [16] on the basis of scaling violations [17] in inclusive charged particle momentum spectra in e^+e^- collisions. However, as discussed in Refs. [17,18], these scaling violations are actually due to threshold production of charmed particles, where, as expected, the region of scaling extends down to lower values of x_F as W is increased.

III. FORMALISM

Hadronic final states in deep inelastic processes are typically analyzed in terms of the usual fragmentation functions D_i^h [3], which parametrize the probability density for producing hadrons h, given an initial state parton of flavor i ($i=u,\bar{u},d,\bar{d},\ldots$). The corresponding formulas for polarized and unpolarized scattering, at leading twist, are well known. However, fragmentation functions are not the most useful quantities in the context of quark flavor tagging. Instead, we define the *quark flavor purity* P_i^h as the probability that a quark of flavor i was probed by the virtual photon, given a final state h. In terms of the usual quantities, we can write

$$P_i^h=\frac{e_i^2 q_i D_i^h}{\Sigma_{i'=f,\bar{f}}\, e_{i'}^2 q_{i'} D_{i'}^h} \tag{1}$$

where e_i are the quark charges, $q_i=q_i(x,Q^2)$ are helicity averaged quark distributions, $D_i^h=D_i^h(x_F,Q^2,x)$ are generalized fragmentation functions,[3] and $\Sigma_{i=f,\bar{f}}P_i^h=1$ holds for any final state. The purities not only have the physically meaningful interpretation mentioned above, but also are the relevant quantities for performing a polarized quark flavor decomposition from semi-inclusive asymmetries.

As a specific example, we consider semi-inclusive deep inelastic scattering with both beam and target longitudinally polarized, where the photon is the exchanged boson. In this case, for hadrons h in the final state, one measures the virtual photon-nucleon asymmetry

$$A^h(x,x_F,Q^2)=\frac{\sigma_{1/2}^h-\sigma_{3/2}^h}{\sigma_{1/2}^h+\sigma_{3/2}^h} \tag{2}$$

where $\sigma_{1/2(3/2)}^h(x,x_F,Q^2)$ denotes the cross section when the projection of the total angular momentum of the photon-nucleon system is $1/2(3/2)$. We can then write any such

[3]For convenience, we integrate over the hadron's p_T and ϕ.

asymmetry (at leading twist) in terms of only purities and quark flavor polarizations $(\Delta q/q)_i$:

$$A^h = \sum_{i=f,\bar{f}} P_i^h \left(\frac{\Delta q}{q}\right)_i . \tag{3}$$

Following the arguments in the previous section, Eq. (3) holds in both the forward and backward regions, for sufficiently hard hadrons. The derivation of Eq. (3) depends crucially on the independence of the fragmentation process on the quark polarization. Although this is usually stated as an additional assumption, it is actually a consequence of the parity invariance of the strong interaction: for inclusive production of unpolarized hadrons, there is no pseudovector observable in the final state that could in principle couple to the quark polarization. It follows that, for example, the presence of target fragmentation does not dilute the asymmetry. In general, there is no reason to minimize the contribution of target fragmentation, as long as the correct purities are used in the analysis.

The form of Eq. (3) allows us to combine several independent asymmetries into a column vector, yielding the matrix equation:

$$\vec{A} = \mathcal{P}\left(\frac{\overrightarrow{\Delta q}}{q}\right). \tag{4}$$

When the matrix elements of $\mathcal{P}$ are determined (from data or simulations), Eq. (4) contains *all* information needed to extract specified polarized quark distributions from a chosen set of semi-inclusive asymmetries. The inclusive asymmetry, where only the scattered lepton is detected, also contains useful information and can be trivially incorporated within the purity formalism:

$$P_i^{incl} = \frac{e_i^2 q_i}{\sum_{i'=f,\bar{f}} e_{i'}^2 q_{i'}} \tag{5}$$

Within the presented approach, then, the extraction of polarized quark flavor distributions is reduced to optimization, via choice of final (and initial) state hadrons and kinematics, of the purity matrix. Several methods of optimization are suggested in Ref. [6].

We have studied the kinematical dependence of purities for light quark flavors and hadrons, on proton and deuteron targets, using LEPTO-6.1 [20] for event generation and JETSET-7.4 [21] for hadronization. Since the purities are independent of the quark helicities, an unpolarized simulation can be used to generate them. We have used the HERMES kinematics and a parametric model [22] of its acceptance in our simulations (see Ref. [6] for details), applying standard DIS selection cuts of $Q^2 > 1\ \mathrm{GeV}^2$, $W^2 > 4\ \mathrm{GeV}^2$, and $y < 0.85$. The following numerical results therefore apply primarily to the forward region, as HERMES detects mostly forward hadrons. As expected from the form of Eq. (1), the

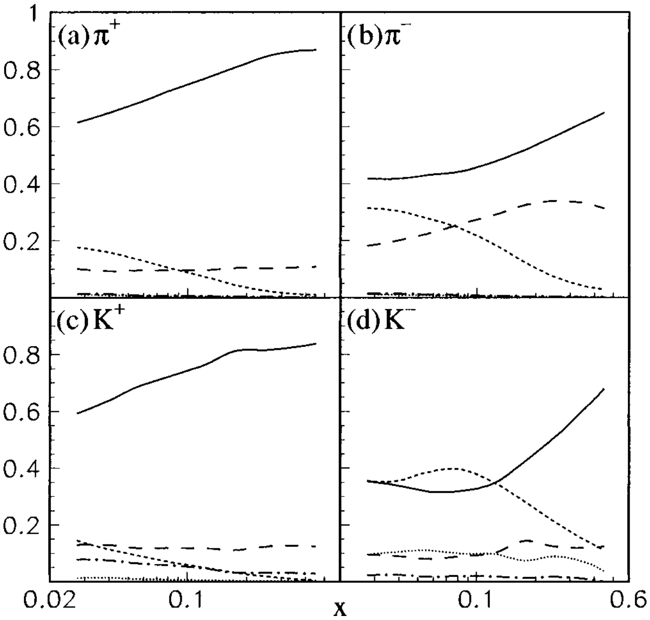

FIG. 1. Purities $P_f^h(x,|x_F|>0.1)$ for typical final states with respect to the light quark flavors: u (solid), $\bar{u}$ (short-dashed), d (long-dashed), s (dotted), and $\bar{s}$ (dot-dashed). The $\bar{d}$-quark contribution never exceeds 10% and is not shown.

purities are relatively insensitive to the choice of hadronization model parameters and unpolarized parton distributions.

In Fig. 1, we plot quark flavor purities for typical final states as a function of the Bjorken-x variable, using a deuteron target (results on the proton are qualitatively similar). All quark flavor labels refer to the proton, using isospin symmetry. The cut $|x_F|>0.1$ is applied to suppress very central hadrons. Using the purities shown, it is straightforward to quantify the sensitivity of semi-inclusive asymmetries to the light quark and antiquark flavors. We summarize our general conclusions here. As expected from charge counting, positively charged hadrons are primarily sensitive to the u-quark [see Figs. 1(a),(c)]. Given that the inclusive asymmetry on a proton target essentially probes the combination $\Delta u + \Delta\bar{u}$, one can reasonably constrain the u- and $\bar{u}$-quark polarizations from a combined analysis of inclusive and positively charged hadron data alone. Since $P_f^{\pi^-}$ is dominated by u-, $\bar{u}$-, and d-quarks at small $x<0.1$ [see Fig. 1(b)], including A^{π^-} in the above analysis allows one to extract $\Delta u/u$, $\Delta\bar{u}/\bar{u}$, and $\Delta d/d$ in the sea region. In addition, as only u- and d-quarks contribute significantly to $P_f^{\pi^-}$ in the valence region ($x>0.2$), one can extract $\Delta u/u$ and $\Delta d/d$ (at large x) using *only* A^{π^+} and A^{π^-}. We conclude that a combination of asymmetries using copiously produced hadrons can be used to extract $\Delta u/u$, $\Delta\bar{u}/\bar{u}$, and $\Delta d/d$. On the other hand, it will be a challenge to measure the polarization of $\bar{d}$-quarks, since the corresponding purities never exceed 10% for the final states shown in Fig. 1. We suggest combining Δd with a measurement of Δd_v $(\equiv \Delta d - \Delta\bar{d})$ using the pion charge dif-

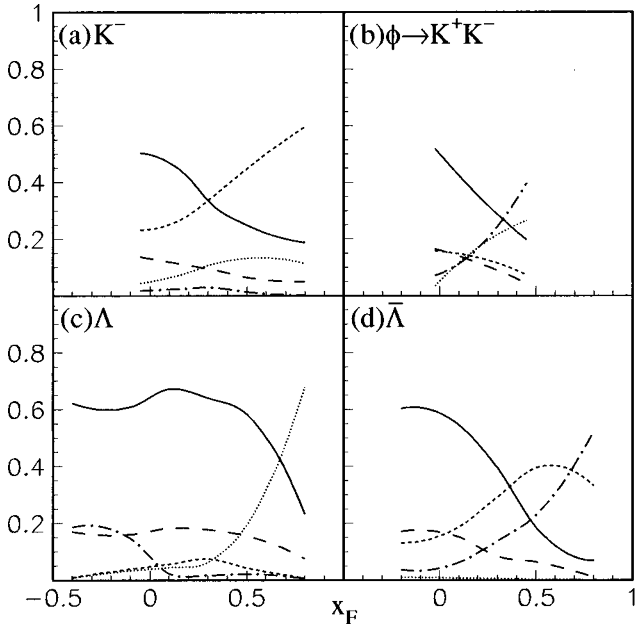

FIG. 2. Purities $P_f^h(x_F, x<0.1)$ for strange hadrons with respect to the light quark flavors: u (solid), $\bar{u}$ (short-dashed), d (long-dashed), s (dotted), and $\bar{s}$ (dot-dashed). The $\bar{d}$-quark contribution never exceeds 10% and is not shown. In (b), the x_F variable refers to the daughter K^+.

ference asymmetry method of Ref. [4].[4]

We have also studied the sensitivity of semi-inclusive asymmetries to polarized strange quarks and antiquarks in the nucleon. In Fig. 2, we plot the purities of selected strange hadrons as a function of x_F in the sea region ($x<0.1$). The K^- is often regarded as an interesting probe of the nucleon, as it is an ''all sea'' object. We indeed find a large sensitivity to sea quarks. As expected from charge counting, the $\bar{u}$-quark dominates over the s-quark contribution, independently of x_F [see Fig. 2(a)]. On the other hand, selecting charged kaons from ϕ meson decay provides improved sensitivity to s- and $\bar{s}$-quarks [see Fig. 2(b)]. For example, using the cuts $x<0.1$ and $x_F>0.1$, we find that $P_s^\phi + P_{\bar{s}}^\phi \simeq 40-45\%$. The ϕ meson may therefore be a useful probe of the polarized strange sea, provided one applies kinematical cuts to suppress elastic production.

Semi-inclusive Λ ($\bar{\Lambda}$) asymmetries are predominantly sensitive to u- (u- and $\bar{u}$-) quark polarizations, except at rather large values of x_F [see Figs. 2(c),(d)]. However, we find that the Λ is sensitive, at the 20% level, to $\bar{s}$-quarks at slightly negative $x_F<-0.2$, where the event rate is still reasonably large. The key point is that the Λ asymmetry in this region is determined essentially by $\Delta u/u$, $\Delta d/d$, and $\Delta\bar{s}/\bar{s}$ (and the corresponding purities). Since $\Delta u/u$ and $\Delta d/d$ will be well constrained by charged hadron and inclusive asymmetries (as discussed above), Λ production in the backward region may be used to constrain the polarized $\bar{s}$-quark sea. In this case, to a good approximation, one can write

$$\frac{\Delta\bar{s}}{\bar{s}} \simeq \frac{1}{P_{\bar{s}}^{\Lambda}}\left[A^{\Lambda} - \sum_{i=u,d} P_i^{\Lambda}\left(\frac{\Delta q}{q}\right)_i\right]. \tag{6}$$

Likewise, as the Λ event rate distribution in x_F is rather broad, one obtains appreciable sensitivity to polarized s-quarks using only a modest cut on x_F. In particular, for $x_F>0.25$ (and $x<0.1$), we find that $P_u^\Lambda \simeq 55\%$ and $P_s^\Lambda \simeq P_d^\Lambda \simeq 20\%$. Hence, given the contribution of u- and d-quarks, the Λ asymmetry in this region probes $\Delta s/s$. We therefore emphasize the importance of measuring Λ asymmetries in *both* the forward and backward regions.

IV. OTHER APPLICATIONS

Thus far, we have introduced the quark flavor purities with particular emphasis on their key role in interpreting electroproduction of unpolarized hadrons, where both beam and target are longitudinally polarized. However, it is clear that our considerations generalize directly to all sufficiently hard hadronic processes. In general, the purities allow us to quantify, in a well defined way, the sensitivity of chosen hadrons to the flavor of quarks involved in the hard scattering process. For the special case of polarization in the initial state, the purities relate, within the framework of a compact formalism, hadron-level asymmetries to the polarization of initial state partons. For example, one may imagine using the purity formalism to measure the polarization of various quark flavors using identified hadrons in electroweak interactions, where parity violation provides polarization observables for free. We leave these possibilities to future work. We will focus instead on one example of particular interest in spin physics: deep inelastic production of polarized hadrons (or jets).

It is well known that polarized quarks can give rise to parity-odd correlations in the final state [24]. We illustrate here how virtual photoproduction of vector polarized final states (see Ref. [25]) can be conveniently analyzed using a formalism based on purities. Our results, written explicitly for virtual photon-nucleon scattering, generalize trivially for other hard hadronic processes. For definiteness, we choose a helicity basis oriented along the virtual photon direction $(+\hat{z})$ and neglect finite angle effects, so that the fragmentation helicity basis is collinear with the quark helicity basis. We then combine the polarizations $\rho^h\hat{z}$ of chosen final states h (possibly specified by kinematics and choice of target) into a column vector $\vec{\rho}=(\{\rho^h\})$. Our result is that at leading twist, for an *unpolarized* beam incident on a target with longitudinal polarization $+\hat{z}$,

$$\vec{\rho} = \Delta\mathcal{P}\left(\frac{\overrightarrow{\Delta q}}{q}\right) \tag{7}$$

where the matrix elements of $\Delta\mathcal{P}$ are defined by

[4]The derivation in Ref. [4] assumes charge and isospin conjugation symmetries for the fragmentation functions, which are formally violated in a complete QCD description of DIS. Phenomenological consequences are studied in Ref. [23].

$$\Delta P_i^h = P_i^h \left(\frac{\Delta D}{D} \right)_i^h . \tag{8}$$

The ΔD_i^h are helicity difference fragmentation functions, which are assumed to be related, modulo dilution factors, to the quark helicity structure of the final state. Also, just as the purities satisfy the constraint $\Sigma_{i=f,\bar{f}} P_i^h = 1$, the quantities ΔP_i^h that enter Eq. (7) are normalized by the longitudinal hadron polarizations $\rho^h \hat{z}$ using a *polarized* beam $(+\hat{z})$ and an *unpolarized* target:

$$\rho^h = \sum_{i=f,\bar{f}} \Delta P_i^h . \tag{9}$$

Equations (7) and (8) also hold for transversely polarized hadrons produced off a transversely polarized target, provided we everywhere make the replacement $\Delta \rightarrow \Delta_\perp$ (helicity→transversity). Indeed, formulas such as Eqs. (7)–(9) are generic to processes with polarization observables in the final state, where the $(\Delta D/D)_i^h$ are the corresponding analyzing powers. We therefore conclude that the purities previously defined are also the natural quantities for performing a global analysis of *polarized* hadron (or jet) production in hard processes.

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