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 asymmetries. Within the context of the presented formalism, we quantify the sensitivity of various semi-inclusive hadron asymmetries to the light quark flavors. We also highlight several applications of our formalism, particularly to measurements intended to probe further the spin structure of the nucleon.

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 lepton production 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 hadronic process, and other applications are mentioned in Section 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. Especially interesting is the role of heavy flavors. Perhaps more importantly, semi-inclusive processes allow to separate [4,5] contributions with definite charge conjugation symmetry. Though it is conventional to define the quark sea contribution to be charge conjugation even, there is no symmetry in the QCD Lagrangian that allows us to relate quark and antiquark distributions in a hadron. The observed violation [6] of the Gottfried sum rule indicates that nonperturbative effects are large for the light quarks, and recent considerations suggest [7] that strange, and even charm, quark distributions in a nucleon may have significant intrinsic components. A comparison of \( C = +1 \) and \( C = -1 \) observables is also interesting since gluon distributions can only couple to \( C = +1 \) observables. It has been recently suggested [8] that a comparison of the \( C = +1 \) and \( C = -1 \) parts of parton helicity and transversity distributions may yield new information on the polarized gluon contribution to the nucleon spin.

Despite this importance of semi-inclusive measurements in hard hadronic processes, particularly polarized deep inelastic scattering, there does not exist a general formalism for the combined analysis of data with arbitrary final states. The extraction of polarized parton distributions from semi-inclusive DIS has been confined to the use of certain leading hadrons to “tag” dominant quark flavors and/or the use of simplifying assumptions for the parton distribution and fragmentation functions. Clearly, this allows only limited information about parton spin distributions to be obtained from data. Moreover, several of the standard assumptions are not strictly valid or require stringent kinematical cuts (see Section II). Hence, it is useful to have a formalism whose generality is independent of the validity of those approximations. In Section III, we introduce a general method to extract chosen polarized quark distributions from an arbitrary combination of hadron asymmetries, independent of kinematics. This new approach is particularly useful in light of the latest generation of existing (HERMES, SMC, TJN AF) and forthcoming (COMPASS, ELFE, HERA-\( p \), RHIC Spin) experimental efforts, which allow detection 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.

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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\footnote{Sophisticated hadronization models, such as the string and cluster models, reflect this fact.}. 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 \cite{9}. We further argue that, generally speaking, there is no \textit{a priori} reason to minimize the effects of target fragmentation. Indeed, it has been shown \cite{9} that, independent of a transverse momentum cut, all collinear singularities for finite hadron energies can be factorized into so-called fracture functions \cite{10} $M_{iN}(x, x_F, Q^2)$, which give the joint probability of “finding” within the target $N$ a parton $i$ and hadron $h$, as a function of the usual variables $x$, $x_F$, and $Q^2$. Future measurements in the target region are important because they offer complementary information on the nucleon state \cite{11} and additional insights into a unified view \cite{12} of hadronic reactions.

Since the fragmentation process, where colored partons are transformed into colorless hadrons, is intrinsically nonperturbative, it has been necessary to resort to phenomenological models. However, all hadronization models, and consequently all jet algorithms, are based on the weak version of local parton-hadron duality (LPHD) \cite{13}, 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 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 \textit{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.

As is well known, 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 \cite{14}. 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 \cite{15}, and indeed, hadron spectra in the central region are found to be very similar \cite{16} in $pp$, $pp$, photoproduction, and low-$x$ DIS processes. These generic features of hadronic final states have been recognized \cite{17,14} 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 \cite{8} the correlations of pions 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 \textit{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 $y$ (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 the low $z$ domain).

In our calculations, we find that at small $|x_F| < 0.1 - 0.2$ and \textit{fixed} $Q^2$, both the current and target correlations decrease as $W$ increases\footnote{Several quantitative examples were given in Ref. \cite{18} on the basis of scaling violations \cite{19} in inclusive charged particle momentum spectra in $e^+e^-$ collisions. However, as discussed in \cite{19,20}, 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.}. 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 \textit{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 \cite{21}. This is an important result, because it illustrates that independent of the effects of the target remnant, there are kinematical effects in the forward region that cannot be described by (current) 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 $(\ln W)^{-1}$). 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.
Inclusive hadron data in DIS and $e^+e^-$ collisions are usually analyzed under the assumptions of charge and isospin conjugation symmetry for the fragmentation functions. Charge symmetry, in particular, is a natural assumption in $e^+e^-$ physics, since quark and antiquark jets are typically inseparable. On the other hand, charge symmetry is broken by perturbative QCD, since just as in the case of parton distributions, flavor singlet and non-singlet fragmentation functions satisfy different evolution equations. Additionally, the presence of significant target correlations, in the case of DIS, may lead to strong violations of the above assumptions. The combined effects of target fragmentation and QCD evolution are predicted [22] to have large effects on semi-inclusive asymmetries in DIS, particularly the well known charge difference asymmetries [4]. In simulations of DIS fragmentation functions, we find significant violations of charge symmetry, even for large values of $x_F$ and $W$. This observation appears to be largely due to the fact that hadronization models inevitably distinguish between valence and sea quarks in the initial state: sea quark fragmentation requires the breakup of at least two color singlet systems, whereas valence quark fragmentation can proceed via breakup of just one. It remains to be seen whether this is a generic artifact of the simulation codes or a physical effect.

In summary, from the point of view of quark flavor tagging, the relevant issue is the degree of correlation between the observed hadron (or event topology) and the quantum numbers of the primary partons. A particularly interesting example is the production of hadrons with conserved quantum numbers (such as strangeness) not intrinsic to the initial hadronic states. In this case, hadrons produced in the forward and backward regions may be strongly correlated (e.g., in $\gamma p \to K^+ \Lambda X$). Then certainly our ability to use the production of, say, the $K^+$ in the forward region to tag the quark flavor implies that the $\Lambda$ can be used as well. 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.

### III. FORMALISM

Hadronic final states in deep inelastic processes are typically analyzed in terms of the usual fragmentation functions $D^h_i$ [3], which parameterize 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 formulae 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 $P^h_i$ 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

$$P^h_i = \frac{e_i^2 q_i D^h_i}{\sum_{i'=f,\bar{f}} e_{i'}^2 q_{i'} D^h_{i'}}$$

(1)

where $e_i$ are the quark charges, $q_i = q_i(x, Q^2)$ are helicity averaged quark distributions, $D^h_i = D^h_i(x_F, Q^2, x)$ are generalized fragmentation functions, and $\sum_{i=f,\bar{f}} P^h_i = 1$ 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

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

(2)

where $\sigma^h_{1/2(3/2)}(x, x_F, Q^2)$ 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 asymmetry (at leading twist) in terms of only purities and quark flavor polarizations $(\Delta q/q)_i$:

$$A^h = \sum_{i=f,\bar{f}} P^h_i \left( \frac{\Delta q}{q} \right)_i$$

(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:

$$\vec{A} = \mathbf{P} \left( \frac{\Delta q}{q} \right)$$

(4)

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3For convenience, we integrate over the hadron’s $p_t$ and $\phi$. 

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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:

\[
P_{i}^{\text{incl}} = \frac{c_i^2 q_i}{\sum_{i'=f,j} c_{i'}^2 q_{i'}} \tag{5}\]

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. [8].

We have studied the kinematical dependence of purities for light quark flavors and hadrons, on proton and neutron targets, using LEPTO-6.1 [23] for event generation and JETSET-7.4 [24] for hadronization. Since the purities are independent of the quark helicities, an unpolarized simulation can be used to generate the purity matrix. We have used the HERMES kinematics and a parametric model [25] of its acceptance in our simulations (see Ref. [8] for details). The following numerical results therefore apply primarily to the forward region, as HERMES detects essentially only forward hadrons. As expected from the form of Eq. (1), the purities are relatively insensitive to the choice of hadronization model parameters and unpolarized parton distributions.

Several quark flavor purities of interest are plotted in the Appendix of Ref. [8]. We only summarize our key results here, emphasizing the potential to extract the light quark and antiquark flavors from the hadrons most abundantly produced in DIS experiments. For both proton and neutron targets, and consequently all neutral targets in the incoherent approximation, the \( \pi^+ \) and \( K^+ \) are predominantly sensitive to \( u \)-quarks, with \( P_{\pi^+}^u \sim P_{K^+}^u \sim 70 – 85\% \) at \( x = 0.1 \), essentially independent of a minimum cut on \( z \). Since \( P_{\pi^+}^{\pi^+,K^+} \lesssim 20\% \) \((f \neq u)\) for all \( x \), to a good approximation we can write \( A^{\pi^+,K^+} \sim \Delta u/u \). The purities \( p_f \) are quantitatively very similar to \( P_{\pi^+}^{\pi^+,K^+} \), except for a neutron target, where the \( d \)-quark becomes important for increasing \( x \): \( P_{\pi^+}^d \sim P_{K^+}^d \sim 40 – 50\% \) at \( x \approx 0.4 \). As the inclusive asymmetry is largely sensitive to \( u + \bar{u} \), we can already reasonably separate the \( u \) and \( \bar{u} \) contributions from a combined analysis of inclusive and positively charged hadron data. One may further optimize the analysis by including asymmetries of negatively charged hadrons, particularly \( A^{\bar{u},K^+} \) but also \( A^{u} \) at low \( x \ll 0.1 \), which are strongly sensitive to the \( \bar{u} \)-quark.

The purity \( P_{d}^{\pi^-} \) is substantially lower than its isospin conjugate \( P_{u}^{\pi^+} \), primarily since \( c^2_d \ll c^2_u \). Even at large \( x > 0.1 \) on a neutron target, \( P_{d}^{\pi^-} \approx 40 – 70\% \) for corresponding cuts on \( z > 0.1 – 0.6 \). At lower values of \( x < 0.1 \), we find \( P_{d}^{\pi^-} \sim P_{u}^{\pi^+} \sim P_{u}^{\pi^-} \sim 20 – 40\% \). The \( K_s \) is also a good probe of the \( d \)-quark; for \( z > 0.1 \) using a neutron target, we find that \( P_{d}^{K_s} \approx 40 – 85\% \) at increasing values of \( x = 0.02 – 0.5 \). One might expect the \( K_s \) to be sensitive to the polarized strange sea. However, we find that independently of \( x \), \( P_{s}^{K_s} \lesssim 25\% \) even with cuts as high as \( z > 0.6 \). Likewise, 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. Trivially, due to its charge the \( \bar{u} \) has the largest purity, up to \( 60\% \) for \( z > 0.6 \) and \( x \approx 0.1 \). The corresponding sensitivity to the \( s \)-quark is quite small: \( P_{s}^{K^-} \approx 10 – 15\% \). On the other hand, we find that approximately half of forward \( \phi \) mesons originate from reactions off \( \text{strange} \) quarks and antiquarks. The \( \phi \) meson may therefore be a useful probe of the strange sea, provided one applies kinematical cuts to suppress elastic production. It will be a challenge to accurately measure the contribution of \( d \)-quarks, since the corresponding purities are less than \( 10–15\% \) for all relevant hadrons. However, it follows from our discussion that a combination of several asymmetries using copiously produced hadrons can be used to extract \( \Delta u/u, \Delta \bar{u}/\bar{u} \), and \( \Delta d/d \). Then, incorporating the inclusive asymmetry in the analysis may enable one to probe the other flavor contributions of interest [4].

**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. Jet handedness and various azimuthal asymmetries have been proposed [26], though unfortunately thus far the analyzing powers have been found to be very small. In the case of identified final states, the \( \Lambda \) and \( \bar{\Lambda} \) hyperons are unique among light hadrons in that the (vector) polarization can be easily reconstructed from their dominant
decay $\Lambda, \bar{\Lambda} \to \pi N$. We illustrate here how virtual photoproduction of polarized $\Lambda$'s can be conveniently analyzed using the purity formalism, following the results of Ref. [27] at leading twist. As before, we combine several (hyperon) polarizations, also specified by kinematics and choice of target, into a column vector $\vec{\rho}$. For definiteness, we choose a helicity basis oriented along the beam direction ($\hat{z}$) and neglect finite angle effects. Then, the hadrons’ longitudinal polarizations $\vec{\rho}$ for “transverse” (helicity $= \pm 1$) photons incident on a longitudinally polarized target can be written compactly as

$$\vec{\rho} = \hat{z} \Delta P \left( \frac{\Delta q}{q} \right)$$  \hspace{1cm} (6)

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

$$\Delta P_i^h = P_i^h \left( \frac{\Delta D}{D} \right)_i^h$$  \hspace{1cm} (7)

The $\Delta D_i^h$ are (hitherto unknown) helicity difference fragmentation functions, which are presumably related, modulio dilution factors, to the quark helicity structure of the hadron $h = \Lambda, \bar{\Lambda}$ [27]. However, just as the purities satisfy the constraint $\sum_{i=f, \bar{f}} P_i^h = 1$, the quantities $\Delta P_i^h$ that enter Eq. (6) are normalized by the longitudinal hadron polarizations $\rho^h$ for scattering off unpolarized targets:

$$\rho^h = \hat{z} \sum_{i=f, \bar{f}} \Delta P_i^h$$  \hspace{1cm} (8)

Eqs. (6-8) also hold for transversely polarized hadrons produced off a transversely polarized target, provided we everywhere make the replacement $\Delta \to \Delta_\perp$ (helicity $\to$ transversity). Indeed, formulae such as Eqs. (6-8) 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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