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Asymmetric Quark/Antiquark Hadronization in e^+e^- Annihilation *

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Abstract

We point out that the fragmentation of a strange quark into nucleons versus antinucleons is not necessarily identical $D_{p/s}(z, Q^2) \neq D_{\bar{p}/s}(z, Q^2)$, even though the perturbative contributions from gluon splitting and evolution are $p \leftrightarrow \bar{p}$ symmetric. The observation of such asymmetries in the hadronization of strange and other heavy quarks can provide insight into the nonperturbative mechanisms underlying jet fragmentation in QCD.

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1 Introduction

A standard assumption often made in the analysis of sea quark distributions is that the strange and antistrange contributions to the nucleon structure functions are identical: $s(x, Q^2) = \bar{s}(x, Q^2)$. Although the perturbative QCD contributions generated from gluon splitting $g \rightarrow s\bar{s}$ and PQCD evolution do have this property, the input distributions associated with the intrinsic bound-state structure of the nucleon wavefunction need not be $s \leftrightarrow \bar{s}$ symmetric. For example, the nonvalence quark distributions associated with the $K\Lambda$ intermediate state, the lowest mass meson-baryon fluctuation containing an intrinsic strange quark-antiquark pair in the nucleon, have the property that the s quark has a harder Bjorken x distribution than the \bar{s} antiquark[1]. Furthermore, due to the angular momentum properties of the $|K\Lambda\rangle$ intermediate state, the s quark helicity is antialigned with that of the parent nucleon and the \bar{s} helicity is unaligned. We have recently presented a quantitative model of the strange and charm distributions and their quark/antiquark asymmetries which is based on power-law or Gaussian mass-weighted distributions of the interpolating meson-baryon states in the nucleon light-cone Fock state wave function [1]. The resulting asymmetry of the strange sea also allows the nucleon to have additional nonzero $C = -1$ moments such as $s - \bar{s}$ contributions to the slope of the proton's charge radius and magnetic moment.

Gribov and Lipatov [2] have shown that the fragmentation functions $D_{H/q}(z, Q^2)$ measured in quark and jet hadronization at $z \simeq 1$ are related by crossing to the quark distributions $G_{q/H}(x, Q^2)$ measured in deep inelastic scattering processes at $x \simeq 1$. Thus any asymmetry between $G_{s/H}(x, Q^2)$ and $G_{\bar{s}/H}(x, Q^2)$ implies a corresponding asymmetry in strange quark fragmentation: $D_{H/s}(z, Q^2) \neq D_{H/\bar{s}}(z, Q^2)$ and $D_{\bar{H}/s}(z, Q^2) \neq D_{H/s}(z, Q^2)$.

Thus it is possible that a strange quark will fragment differently into a proton versus an antiproton. At first sight this seems antiintuitive since if the strange quark produces a gluon which then hadronizes, the resulting baryon and antibaryon products will be symmetric. If the s quark hadronizes by coupling to a higher Fock component $|uuds\bar{s}\rangle$ of the proton, then there will be no asymmetry for $s \rightarrow pX$ versus $s \rightarrow \bar{p}X$

if the Fock state is symmetric under $s \leftrightarrow \bar{s}$. The quark/antiquark fragmentation asymmetry which we shall discuss in this paper is a consequence of nonperturbative QCD processes where, for example, the strange quark hadronizes via a Λ in an intermediate state which subsequently couples to a proton. Of course, the weak decay of the strange quark is explicitly nucleon/antinucleon asymmetric so that testing for such asymmetries requires that the weak decay products have to be carefully isolated from the hadronization processes. We discuss how this can be done below.

2 Anomalies of the Quark Sea

The quark/antiquark asymmetry of the strange sea of the nucleon is just one of a number of empirical anomalies relating to the composition of the nucleons in terms of their nonvalence sea quarks: the European Muon Collaboration has observed a large excess of charm quarks at large momentum fraction x in comparison with the charm distributions predicted from photon-gluon fusion processes [3]; the large violation of the Ellis-Jaffe sum rule observed at CERN [4, 5] and SLAC [6, 7] indicates that a significant fraction of the proton's helicity is carried by the sea quarks; the violation of the Gottfried sum rule measured by the New Muon Collaboration (NMC) [8] indicates a strong violation of flavor symmetry in the \bar{u} and \bar{d} distributions; furthermore, there are difficulties in understanding the discrepancy between two different determinations of the strange quark content in the nucleon sea [9, 10] assuming conventional considerations [11] and perturbative QCD effects [12].

The “intrinsic” quark-antiquark ($q\bar{q}$) pairs generated by the nonperturbative meson-baryon fluctuations in the nucleon sea [1, 13, 14, 15, 16] are multi-connected to the valence quarks of the nucleon, and thus they have distinct properties from those of the ordinary “extrinsic” sea quarks and antiquarks generated by QCD evolution. The concept of “intrinsic charm” was originally introduced [13] in order to understand the large cross-sections for charmed particle production at high x in hadron collisions, and a recent comparison [17] between the next-to-leading order extrinsic charm and the EMC charm quark structure function measurements confirms the need for intrinsic charm. More recently, intrinsic $q\bar{q}$ pairs of light-flavor u , d and s were studied

using a light-cone meson-baryon fluctuation model [1]. The model predicts significant asymmetries in the momentum and helicity distributions of the quarks and antiquarks of the nucleon sea and provides a consistent framework for understanding the Gottfried and Ellis-Jaffe sum rule violations and the conflict between different measures of strange quark distributions.

Although the quark/antiquark asymmetries for the intrinsic $q\bar{q}$ pairs can explain a number of experimental anomalies [1], there is still no direct experimental confirmation for such asymmetries. The quark/antiquark asymmetries for the light-flavor $u\bar{u}$ and $d\bar{d}$ pairs are difficult to measure since one has the freedom to re-define the sea quarks by the requirements of sea quark/antiquark symmetries due to the excess of net u and d quarks in the nucleon. The quark/antiquark asymmetries for the heavy $b\bar{b}$ and $t\bar{t}$ pairs are small due to the large b and t quark masses. Thus the intrinsic strange $s\bar{s}$ and charm $c\bar{c}$ quark/antiquark asymmetries are the most significant features of the model and the easiest to observe. It will be shown in this work that the hadronic jet fragmentation of the s and c quarks in electron-positron (e^+e^-) annihilation may provide a feasible laboratory for identifying quark/antiquark asymmetries in the nucleon sea.

3 Asymmetric Quark/Antiquark Hadronization

If there are significant quark/antiquark asymmetries in the distribution of the $s\bar{s}$ pairs in the nucleon sea, corresponding asymmetries should appear in the jet fragmentation of s versus \bar{s} quarks into nucleons. For example, if one can identify a pure sample of tagged s jets, then one could look at the difference of $D_{p/s}(z) - D_{\bar{p}/s}(z)$ at large z , where $D_{h/q}(z)$ is the fragmentation function representing the probability for the fragmentation of the quark q into hadron h and z is the fraction of the quark momentum carried by the fragmented hadron.

In the following we will discuss in some detail a test of the strange/antistrange asymmetry of the nucleon sea using the strange quark jets produced in e^+e^- annihilation and then extend our discussion to the case of charm quark jets. A key ingredient for such tests is a source with unequal numbers of quark q and antiquark \bar{q} jets in a

specific direction so that we could identify a pure q (or \bar{q}) jet. Secondly, we require the identification of the detected nucleon which is from the fragmentation of this quark q (or \bar{q}) jet rather than from other sources or subsequent processes. At the Z^0 -boson resonance in e^+e^- annihilation, there is a forward-backward asymmetry A_{BF}^f in the production of fermion pairs $f\bar{f}$. The asymmetries A_{BF}^f for charged-leptons and quarks (light-flavors, c , and b) have been measured to be of the order 10%, in agreement with the predictions of the Standard Model [18]. In case of polarized electron beam, the forward-backward asymmetries are significantly enhanced. From this fact we know that more s (or c) quarks than \bar{s} (or \bar{c}) quarks are produced along the incident electron direction with left-handed polarization. One can insure high $s\bar{s}$ purity by requiring a ϕ meson to be directly produced at large momentum fraction z in the backward-going jet. This is a feature of fragmentation models and is supported by experiment [19]: the ϕ at large z arises dominantly from the combination of the backward \bar{s} quark with an s quark from a produced $s\bar{s}$ pair in the color-field. The forward jet is then predominantly an s quark. Alternatively, if the ϕ is produced at large momentum fraction z in the forward-going jet, then the backward jet is predominantly an \bar{s} quark.

In the meson-baryon fluctuation model of intrinsic $q\bar{q}$ pairs [1], the s quark has a higher momentum fraction than the \bar{s} in the proton wavefunction. Thus we expect that protons are produced at higher momenta from the s quark hadronic fragmentation compared to $\bar{s} \rightarrow p$ fragmentation. By using the high- z ϕ tag, we can insure that the background from other Z^0 decays is small. From symmetry considerations, we should have an excess of $s \rightarrow p$ over $s \rightarrow \bar{p}$ at high momentum fraction in the forward going jet with a backward high- z ϕ , and *vice versa*. Furthermore, we can cut out protons fragmented at small z to amplify the fragmentation asymmetry. Thus the combination and self-consistency of three aspects:

1. the asymmetry between the forward $D_{p/s}(z)$ and $D_{\bar{p}/s}$ with a backward high- z ϕ ;
2. the asymmetry between the backward $D_{\bar{p}/\bar{s}}(z)$ and $D_{p/\bar{s}}$ with a forward high- z ϕ ;

3. the asymmetry between the forward $D_{p/s}(z)$ with a backward high- z ϕ and the backward $D_{p/\bar{s}}(z)$ with forward high- z ϕ

can provide a clean and unambiguous test of the strange-antistrange asymmetry.

Any intermediate QCD hadronization process is allowed in the test of hadronization asymmetries. However, we must avoid counting hadrons which originate from weak decays, such as $s \rightarrow \Lambda X \rightarrow pX$ and $s \rightarrow \Sigma \rightarrow pX$, etc. Fortunately, the hyperons decay through weak interactions with relatively very long life time, and thus their decay products appear at long distances from the production point. For example, the relativistic hyperon decays typically more than 8 cm away from the production point; thus it should be possible to exclude protons from this source.

We now make a rough estimate of the magnitudes for the probability of the fragmentation process $s \rightarrow p$ and the $s \rightarrow p$ versus $s \rightarrow \bar{p}$ asymmetry for the forward going s jet using the Gribov-Lipatov reciprocity relation, which connects the annihilation and deep inelastic scattering (DIS) processes in their physical regions [2, 20, 21]. The fragmentation function $D_{h/q}(z)$ for a quark q splitting into a hadron h is related to the distribution function $q_h(x)$ of finding the quark q inside the hadron h by the reciprocity relation

$$D_{h/q}(z) = x q_h(x), \quad (1)$$

where $z = 2p \cdot q/Q^2$ is the momentum fraction of the produced hadron from the q jet in the annihilation process, and $x = Q^2/2p \cdot q$ is the Bjorken scaling variable in the DIS process. Although there are corrections to this relation from experimental observation and theoretical considerations[21], it can serve as a first estimate of the fragmentation function. The strange quark distribution in the proton, $s_p(x)$, has been evaluated in the light-cone meson-baryon fluctuation model [1], and the agreement with the available data is reasonable. We thus use the calculated $s_p(x)$ in [1] to evaluate the probability of the fragmentation $s \rightarrow p$. We also make a minimum z cut for the protons to reduce possible contamination from the background. For $z_{\text{cut}} = 0.5$ we have $\int_{z_{\text{cut}}}^1 dz D_{p/s}(z) \sim 10^{-4}$, and for $z_{\text{cut}} = 0.6$ the value of $\int_{z_{\text{cut}}}^1 dz D_{p/s}(z)$ will be reduced by two additional orders of magnitude. Despite the crudeness of the model and the limited range of the Gribov-Lipatov reciprocity relation, we expect that the

above estimate should serve as a reasonable guide to the size of the expected effects.

We define the $s \rightarrow p$ versus $s \rightarrow \bar{p}$ asymmetry

$$A_s^{p\bar{p}}(z) = \frac{D_{p/s}(z) - D_{\bar{p}/s}(z)}{D_{p/s}(z) + D_{\bar{p}/s}(z)}, \quad (2)$$

which can be measured through the quantity

$$A_s^{p\bar{p}}(z) = \frac{N[\phi p(z)] - N[\phi \bar{p}(z)]}{N[\phi p(z)] + N[\phi \bar{p}(z)]} / A_{BF}^s, \quad (3)$$

where $N[h_1 h_2]$ represents the number of tagged h_1 and h_2 events under the specified kinematics in e^+e^- annihilation. We normalize the asymmetry to the value of the strange forward-backward asymmetry A_{BF}^s which can be measured by the tagged ϕ and Λ versus $\bar{\Lambda}$ (or strange versus antistrange mesons) events or by tagging high momentum strange versus antistrange hadrons with contributions from other flavors removed [22]. The combination of the ϕ tag on one jet with a strange or antistrange hadron tag on the other side jet can be used to identify the $s\bar{s}$ quark jets as well as identify which jet is s or \bar{s} . The asymmetry $A_s^{p\bar{p}}(z)$ can be enhanced by restricting the analysis to two-jet events since fragmentation from gluon jets will be symmetric. Using the reciprocity relation Eq. (1) we have

$$A_s^{p\bar{p}}(z) = \frac{s_p(z) - \bar{s}_p(z)}{s_p(z) + \bar{s}_p(z)}, \quad (4)$$

from which we can evaluate the asymmetry $A_s^{p\bar{p}}(z)$ from the strange-antistrange asymmetry $s(x)/\bar{s}(x)$ in Ref. [1]. In Fig. 1 we present the calculated $A_s^{p\bar{p}}(z)$ in the light-cone meson-baryon fluctuation model [1] with parameters as those in Fig. 4 of Ref. [1]. The strange and antistrange quark distributions $s_p(x)$ and $\bar{s}_p(x)$ are evaluated by a light-cone two-level convolution formula for the $|K\Lambda\rangle$ component of the nucleon multiplied by a factor $d_v(x)|_{\text{fit}}/d_v(x)|_{\text{model}}$ in the same framework to reflect the effect of QCD evolution. We see that the calculated $A_s^{p\bar{p}}(z)$ asymmetry has a strong z -dependence as a consequence of the corresponding predictions of our model for a significant quark-antiquark asymmetry in the nucleon sea. Thus given sufficient statistics, there should be no difficulty in testing the quark-antiquark asymmetry in the nucleon sea by measuring the predicted z -dependence in the $s \rightarrow p$ versus $s \rightarrow \bar{p}$ asymmetry $A_s^{p\bar{p}}(z)$ through Eq. (3).

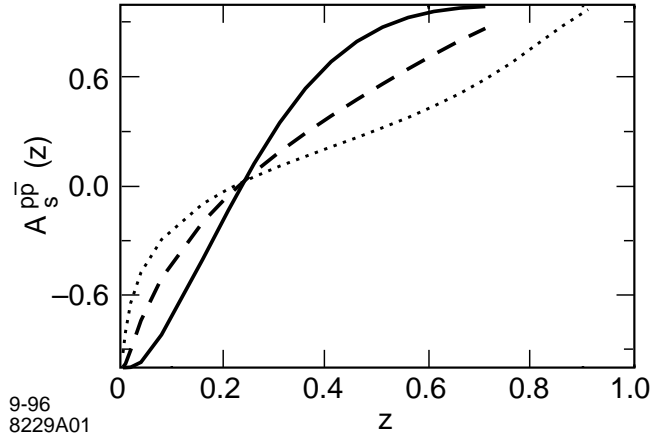


Figure 1: The $s \rightarrow p$ versus $s \rightarrow \bar{p}$ asymmetry $A_s^{p\bar{p}}(z)$ as a function of the momentum fraction z of the produced proton (antiproton) from the s jet. The curves are the calculated results for $A_s^{p\bar{p}}(z)$ in the light-cone meson-baryon fluctuation model with Gaussian wavefunction $\psi_{\text{Gaussian}}(\mathcal{M}^2) = A_{\text{Gaussian}} \exp(-\mathcal{M}^2/2\alpha^2)$ in the invariant mass $\mathcal{M}^2 = \sum_{i=1}^2 \frac{\mathbf{k}_{\perp i}^2 + m_i^2}{x_i}$. The full (dashed) curve is the calculated result of $A_s^{p\bar{p}}(z)$ $\alpha = 330$ (530) MeV. The dotted curve is the result with a larger $\alpha = 800$ MeV adjusted for consistency with the available empirical constraints on the strange-antistrange asymmetry in the proton structure function.

We can extend the above discussion to tests of the charm-anticharm asymmetry in the nucleon sea; for example, one can define the $c \rightarrow p + X + c$ versus $c \rightarrow \bar{p} + X + c$ asymmetry in e^+e^- annihilation at the Z^0 in analogy to $A_s^{p\bar{p}}(z)$. The advantage of charm over strangeness for studying such asymmetries is that:

1. The leading charm quark decays and any protons produced from open charm weak decay can in principle be traced back to the source.
2. The protons associated with charmed meson charmed baryon fluctuations will be fragmented at higher z than the protons which come from simple gluon fluctuations.

Such measurements are feasible for those c (and b) decays where the vertices from the c and \bar{c} decays are displaced and can be measured. We predict a small but nonzero asymmetry for the fragmentation distributions $D_{p/c}(z)$ versus $D_{\bar{p}/c}(z)$ from

the distribution functions $c_p(x)$ and $\bar{c}_p(x)$ in our model of intrinsic $q\bar{q}$ pairs using the Gribov-Lipatov relation, in analogy to the above discussion for the strange jets.

The probability of intrinsic charm quarks in the nucleon sea is estimated [17] to be of the order of $0.6 \pm 0.3\%$, an order of magnitude smaller than that of the strange quark $\sim 5\%$ [1]. Therefore we expect that the fragmentation function $D_{p/c}(z)$ will be reduced by one order of magnitude compared to that of $D_{p/s}(z)$. One can define the $c \rightarrow p + X + c$ versus $c \rightarrow \bar{p} + X + c$ asymmetry in analogy to $A_s^{p\bar{p}}(z)$. It is natural to expect a somewhat smaller z -dependence of the charm asymmetry compared to that of $A_s^{p\bar{p}}(z)$.

4 Conclusion

Electron-positron annihilation, particularly at the Z^0 -resonance, can provide a laboratory for testing nucleon/antinucleon asymmetries in the QCD hadronization of strange and charm quark jets. Such asymmetries are characteristic of intrinsic $q\bar{q}$ pairs in the nucleon wavefunctions. In particular, we predict a significant z -dependence of the $s \rightarrow p$ versus $s \rightarrow \bar{p}$ asymmetry from the hadronization of forward s jets measured through tagged ϕ events under specified conditions. We also suggest a test of the corresponding charm/anticharm hadronization asymmetry through the $c \rightarrow p + X + c$ versus $c \rightarrow \bar{p} + X + c$ processes. The experimental observation of hadronization asymmetries can provide insight into nonperturbative mechanisms in jet fragmentation.

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