PHYSICAL REVIEW D **78,** 054007 (2008)

Antihyperon polarization in high energy pp collisions with polarized beams

Ye Chen,[1] Zuo-tang Liang,[1] Ernst Sichtermann,[2] Qing-hua Xu,[1,2] and Shan-shan Zhou[1]
[1]*Department of Physics, Shandong University, Jinan, Shandong 250100, China*
[2]*Nuclear Science Division,*
Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
(Received 5 July 2007; published 11 September 2008)

We study the longitudinal polarization of the $\bar{\Sigma}^-$, $\bar{\Sigma}^+$, $\bar{\Xi}^0$, and $\bar{\Xi}^+$ antihyperons in polarized high-energy pp collisions at large transverse momenta, extending a recent study of the $\bar{\Lambda}$ antihyperon. We make predictions by using different parameterizations of the polarized parton densities and models for the polarized fragmentation functions. Similar to the $\bar{\Lambda}$ polarization, the $\bar{\Xi}^0$ and $\bar{\Xi}^+$ polarizations are found to be sensitive to the polarized antistrange sea $\Delta\bar{s}(x)$ in the nucleon. The $\bar{\Sigma}^-$ and $\bar{\Sigma}^+$ polarizations show sensitivity to the light sea quark polarizations $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$, and their asymmetry.

DOI: 10.1103/PhysRevD.78.054007 PACS numbers: 13.88.+e, 13.85.Ni, 13.87.Fh

I. INTRODUCTION

The self spin-analyzing parity violating decay [1] of hyperons and antihyperons provides a practical way to determine the hyperon and antihyperon polarization by measuring the angular distributions of the decay products. The polarizations have been used widely in studying various aspects of spin physics in high-energy reactions [2–7]. The discovery of transverse hyperon polarization in unpolarized hadron-hadron and hadron-nucleus collisions in the 1970s led to many subsequent studies, both experimentally and theoretically [8,9]. Phenomenological studies of longitudinal hyperon polarization may be found in Refs. [10–26]. The main themes of these studies can be categorized as follows. On the one hand, one aims to study spin transfer in the fragmentation process. On the other, one aims to get insight in the spin structure of the initial hadrons. Experimental data are available from e^+e^- annihilation at the Z pole [2,3], deep-inelastic scattering with polarized beams and targets [4–7], and proton-proton (pp) collisions [27].

The study of antihyperon polarization remains topical. Recent COMPASS data [7] seem to indicate a difference between Lambda and anti-Lambda polarization. The proton spin physics program at the Relativistic Heavy Ion Collider (RHIC) has come online [28]. A recent study for anti-Lambda polarization in polarized pp collisions [26] shows sensitivity to the antistrange quark spin contribution to the proton spin, which is only poorly constrained by existing data. In this paper, we evaluate the longitudinal polarization of the $\bar{\Sigma}^-$, $\bar{\Sigma}^+$, $\bar{\Xi}^0$, and $\bar{\Xi}^+$ antihyperons in pp collisions at large transverse momenta p_T. Section II contains the phenomenological framework and discusses the current knowledge of the parton distribution and fragmentation functions. The contributions to the antihyperon production cross sections are discussed in Sec. III, followed by results for the polarizations in Sec. IV and a short summary in Sec. V.

II. PHENOMENOLOGICAL FRAMEWORK

The method to calculate the longitudinal polarization of high p_T hyperons and antihyperons in high-energy pp collisions is based on the factorization theorem and perturbative QCD and has been described in earlier works [12,16–21]. For self-containment we briefly summarize the key elements and emphasize the aspects that are specific to antihyperons in the following of this section.

A. Formalism

We consider the inclusive production of high p_T antihyperons ($\bar{H}$) in pp collisions with one of the beams longitudinally polarized. The longitudinal polarization of $\bar{H}$ is defined as

$$P_{\bar{H}}(\eta) \equiv \frac{d\sigma(p_+p \to \bar{H}_+X) - d\sigma(p_+p \to \bar{H}_-X)}{d\sigma(p_+p \to \bar{H}_+X) + d\sigma(p_+p \to \bar{H}_-X)} = \frac{d\Delta\sigma}{d\eta}(\vec{p}p \to \bar{H}X) \Big/ \frac{d\sigma}{d\eta}(pp \to \bar{H}X), \tag{1}$$

where η is the pseudorapidity of the $\bar{H}$, the subscripts $+$ and $-$ denote positive and negative helicity, and $\Delta\sigma$ and σ are the polarized and unpolarized inclusive production cross sections.

We assume that transverse momentum p_T of the produced $\bar{H}$ is high enough so that the cross section can be factorized in a collinear way. In this case, the $\bar{H}$'s come merely from the fragmentations of high p_T partons from $2 \to 2$ hard scattering ($ab \to cd$) with one initial parton polarized, and the polarized inclusive production cross section is given by

$$\frac{d\Delta\sigma}{d\eta}(\vec{p}p \to \bar{H}X) = \int_{p_T^{\min}} dp_T \sum_{\rm abcd} \int dx_a dx_b \Delta f_a(x_a) f_b(x_b) \times D_L^{\vec{a}b\to\vec{c}d}(y) \frac{d\hat{\sigma}}{d\hat{t}}(ab \to cd) \Delta D_c^{\bar{H}}(z), \tag{2}$$

where the transverse momentum p_T of $\bar{H}$ is integrated above a threshold $p_T^{\min}$; the sum concerns all subprocesses; $\Delta f_a(x_a)$ and $f_b(x_b)$ are the polarized and unpolarized parton distribution functions in the proton, x_a and x_b are the momentum fractions carried by partons a and b, $D_L^{\vec{a}b\to\vec{c}d}(y) \equiv d\Delta\hat{\sigma}/d\hat{\sigma}$ is the partonic spin transfer factor in the elementary hard process $\vec{a}b \to \vec{c}d$ with cross section $\hat{\sigma}$, $y \equiv p_b \cdot (p_a - p_c)/p_a \cdot p_b$ is defined in terms of the four momenta p of the partons a-d, and $\Delta D_c^{\bar{H}}(z)$ is the polarized fragmentation function. It is defined by

$$\Delta D_c^{\bar{H}}(z) \equiv D_c^{\bar{H}}(z, +) - D_c^{\bar{H}}(z, -), \quad (3)$$

in which the argument z is the momentum carried by $\bar{H}$ relative to the momentum of the fragmenting parton c, and the arguments $+$ and $-$ denote that the produced $\bar{H}$ has equal or opposite helicity as parton c. The scale dependencies of the parton distribution and fragmentation functions have been omitted for notational clarity. Intrinsic transverse momenta in the proton and in the fragmentation process are small compared with p_T and are not considered above.

The unpolarized inclusive production cross section $d\sigma/d\eta$ is given by an analogous expression with unpolarized parton distribution and fragmentation functions.

B. Inputs

The differential cross section is a convolution of three factors, the parton distribution functions, the cross section of the elementary hard process, and the fragmentation functions. We discuss them separately in the following.

1. The partonic spin transfer factors $D_L^{\vec{a}b\to\vec{c}d}(y)$ in the hard scattering

The partonic spin transfer factor $D_L^{\vec{a}b\to\vec{c}d}(y)$ is determined by the spin dependent hard scattering cross sections, many of which are known at leading and next to leading order [29–31]. The leading order results for $D_L^{\vec{a}b\to\vec{c}d}(y)$ are functions only of y, defined above, and are tabulated in Ref. [18] for quarks. Here, we are particularly interested in antiquarks. By using charge conjugation, a symmetry which is strictly valid in QCD, one obtains

$$D_L^{\vec{\bar{q}}_1 q_2\to\vec{\bar{q}}_1 q_2}(y) = D_L^{\vec{q}_1 q_2\to\vec{q}_1 q_2}(y), \quad (4)$$

$$D_L^{\vec{\bar{q}}_1 g\to\vec{\bar{q}}_1 g}(y) = D_L^{\vec{q}_1 g\to\vec{q}_1 g}(y), \quad (5)$$

etc. Consistency demands that the partonic spin transfer be used with the polarized parton distributions and fragmentation functions of the same order. In view of the current knowledge of the polarized fragmentation functions, we consider only the leading order.

2. The parton distribution functions

The unpolarized parton distribution functions $f(x)$ are determined from unpolarized deep inelastic scattering and other related data from unpolarized experiments. Many parametrizations exist also for the polarized parton distribution functions $\Delta f(x)$, e.g., GRSV2000, BB, LSS, GS, ACC, DS2000, and DNS2005 [32–38]. However, they are much less well constrained by data and large differences exist, in particular, for the parameterizations of the polarized antisea distributions. This is illustrated in Fig. 1,

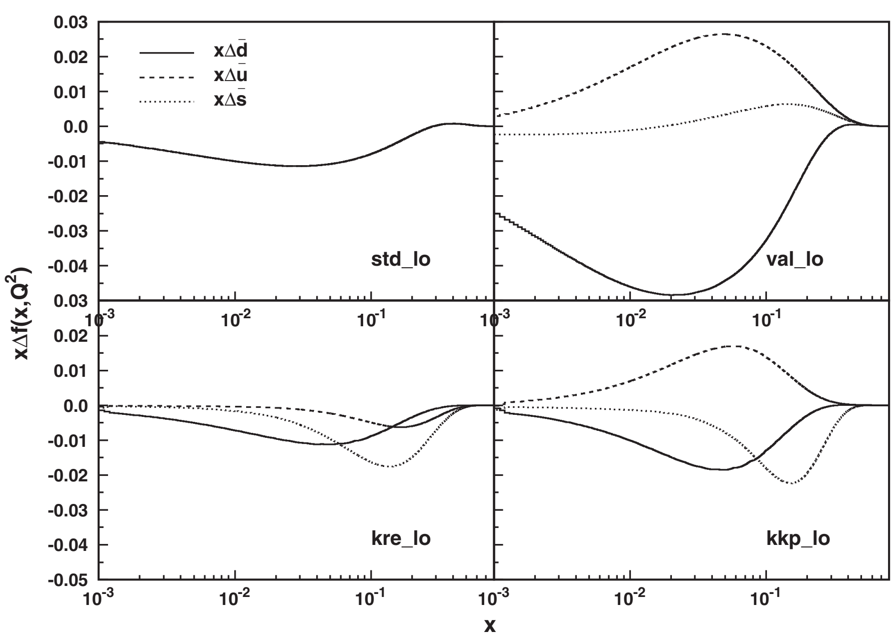

FIG. 1. Polarized antisea quark distributions from the leading order GRSV2000 (upper) and DNS2005 (lower) parameterizations evaluated at a scale $Q = 10$ GeV.

where the antisea distributions from the GRSV2000 [32] and DNS2005 [38] parametrizations are shown.

3. The polarized fragmentation functions $\Delta D_c^{\bar{H}}(z)$

The polarized fragmentation functions $\Delta D_c^{\bar{H}}(z)$ are defined in Eq. (3) and represent the difference of the probability densities for finding an antihyperon $\bar{H}$ in a parton c with equal and opposite helicity as parton c. They have been studied experimentally in e^+e^- annihilation, polarized deep-inelastic scattering, and high p_T hadron production in polarized pp collisions, but present data [2–7,27] do not provide satisfactory constraints. It is thus necessary to make an *Ansatz* or model.

Several *Ansätze* have been adopted in the literature [13–15,23]. One possibility is to relate $\Delta D_c^{\bar{H}}(z)$ to the unpolarized fragmentation functions $D_c^{\bar{H}}(z)$ by means of spin transfer coefficients. Alternatively, one could use the Gribov relation [39], a proportionality relating $D_c^{\bar{H}}(z) \propto q_c^{\bar{H}}(z)$ and $\Delta D_c^{\bar{H}}(z) \propto \Delta q_c^{\bar{H}}(z)$ in which $q_c^{\bar{H}}(z)$ and $\Delta q_c^{\bar{H}}(z)$ are the parton distributions in the (anti-)hyperon. Other approaches to $\Delta D_c^{\bar{H}}(z)$ are in essence often different combinations or approximations of the aforementioned approaches. Although this paper is focused on the leading order, it should be noted that in general the distributions depend also on the scale Q^2. The Q^2 evolutions of the distributions are generally different, and *Ansätze* of this type are thus necessarily made at specific values of Q^2. The $\bar{H}$ sample produced in experiment consists of the QCD contributions and of contributions from electromagnetic or electroweak decays of heavier resonances. The latter are not formally part of the cross sections in the factorized framework, but do need to be considered in comparisons between theory and experiment.

In this paper, we use the Lund string fragmentation model [40] to describe the hadronization process and hence to evaluate the probability densities expressed by the fragmentation functions. This model enables us to distinguish between directly produced $\bar{H}$ and $\bar{H}$, which are decay products of heavier resonances and, furthermore, to distinguish between $\bar{H}$ that contain the initial parton c and those that do not. It should be noted that Lund string fragmentation is in general not equivalent to the independent fragmentation in the factorized framework, and the fragmentation probability densities are not necessarily universal. We expect that such effects are numerically unimportant for the $\bar{H}$ considered in this paper, $\bar{H}$ produced at central rapidities with large p_T in polarized pp collisions at RHIC, and have verified explicitly for the $\bar{\Lambda}$ in these conditions that indeed the same (anti-)quark fragmentation probabilities are found as in a kinematically equivalent colliding e^+e^- system.

Keeping the notation, we thus express polarized fragmentation function as the sum of contributions from directly produced and from decay $\bar{H}$

$$\Delta D_c^{\bar{H}}(z) = \Delta D_c^{\bar{H}}(z; \text{direct}) + \Delta D_c^{\bar{H}}(z; \text{decay}), \quad (6)$$

and evaluate the decay contribution $\Delta D_c^{\bar{H}}(z; \text{decay})$ by a sum over parent antihyperons $\bar{H}_j$ and kinematic convolutions

$$\Delta D_c^{\bar{H}}(z; \text{decay}) = \sum_j \int dz' t^D_{\bar{H},\bar{H}_j} K_{\bar{H},\bar{H}_j}(z, z') \Delta D_c^{\bar{H}_j}(z'), \quad (7)$$

in which the kernel function $K_{\bar{H},\bar{H}_j}(z, z')$ is the probability for the decay of the parent $\bar{H}_j$ with a fractional momentum z' to produce $\bar{H}$ with fractional momentum z, and $t^D_{\bar{H},\bar{H}_j}$ is the spin transfer factor in the decay process.

Most of the decay processes involved here are two body decay $\bar{H}_j \to \bar{H}\bar{M}$. For an unpolarized two body decay, the kernel function $K_{\bar{H},\bar{H}_j}(z, z')$ can easily be calculated and is the same as that for $H_j \to HM$. In this case, the magnitude of the momentum of H is fixed, and the direction is isotropically distributed in the rest frame of the parent H_j. A Lorentz transformation to the moving frame of H_j gives

$$K_{H,H_j}(z, \vec{p}_T; z', \vec{p}_T') = \frac{N}{E_j} \mathrm{Br}(H_j \to HM) \delta(p \cdot p_j - m_j E^*), \quad (8)$$

where $Br(H_j \to HM)$ is the decay branching ratio, N is a normalization constant, and E^* is the energy of H in the rest frame of H_j, which depends on the parent mass m_j and on the masses of the decay products. The corresponding calculation of $K_{H,H_j}(z, z')$ for a *polarized* H_j is more involved since the angular decay distribution can be anisotropic in the case of a weak decay, and each decay process needs to be dealt with separately. However, since the E^* is usually small compared with the momentum of H_j in the pp center-of-mass frame, the anisotropy can be neglected, and Eq. (8) forms a good approximation.

The decay spin transfer factors for hyperons $H_j \to H + X$ are discussed and given, e.g., in Refs. [11,17]. Charge conjugation is a good symmetry for these decays, and hence $t^D_{\bar{H},\bar{H}_j} = t^D_{H,H_j}$. Furthermore, $\Delta D_c^{\bar{H}}(z; \text{direct}) = \Delta D_{\bar{c}}^{H}(z; \text{direct})$, so that only $\Delta D_c^{H}(z; \text{direct})$ need to be modeled. The main strong decay contributions are those from $J^P = (3/2)^+$ hyperons, such as $\Sigma^* \to \Sigma\pi$, and $\Xi^* \to \Xi\pi$. The electromagnetic and weak decay contributions, for example $\Sigma^0 \to \Lambda\gamma$ and $\Xi \to \Lambda\pi$, can be evaluated analogously, and we will include these contributions in our results.

Our aforementioned classification follows Refs. [11,12,16–19] and distinguishes (A) directly produced hyperons that contain the initial quark q of flavor f; (B) decay products of heavier polarized hyperons; (C) directly produced hyperons that do not contain the initial q; (D) decay products of heavier unpolarized hyperons. Therefore,

$$D_f^H(z;\text{direct}) = D_f^{H(\text{A})}(z) + D_f^{H(\text{C})}(z) \quad (9)$$

for the unpolarized fragmentation functions and, similarly, for the polarized fragmentation functions

$$\Delta D_f^H(z;\text{direct}) = \Delta D_f^{H(\text{A})}(z) + \Delta D_f^{H(\text{C})}(z). \quad (10)$$

We assume that directly produced hyperons that do not contain the initial quark are unpolarized, so that

$$\Delta D_f^{H(\text{C})}(z) = 0. \quad (11)$$

The polarization of directly produced hyperons then originates only from category (A) and is given by

$$\Delta D_f^{H(\text{A})}(z) = t_{H,f}^F D_f^{H(\text{A})}(z), \quad (12)$$

in which $t_{H,f}^F$ is known as the fragmentation spin transfer factor. If the quarks and antiquarks produced in the fragmentation process are unpolarized, consistent with Eq. (11), then $t_{H,f}^F$ is a constant given by

$$t_{H,f}^F = \Delta Q_f / n_f, \quad (13)$$

where ΔQ_f is the fractional spin contribution of a quark with flavor f to the spin of the hyperon, and n_f is the number of valence quarks of flavor f in H. In recursive cascade hadronization models, such as Feynman-Field type fragmentation models [41], where a simple elementary process takes place recursively, $D_f^{H(A)}(z)$ and $D_f^{H(C)}(z)$ are well defined and determined. In such hadronization models, $D_f^{H(A)}(z)$ is the probability to produce a first rank H with fractional momentum z. This probability is usually denoted by $f_{q_f}^H(z)$ in these models, so that $D_f^{H(C)}(z) = D_f^H(z;\text{direct}) - f_{q_f}^H(z)$, and $f_{q_f}^H(z)$ is well determined by unpolarized fragmentation data. Hence, in such models the z dependence of the polarized fragmentation functions ΔD is obtained from the unpolarized fragmentation functions, which are empirically known. The only unknown is the spin transfer constant $t_{H,q}^F = \Delta Q_f / n_f$. By using either the SU(6) wave function or polarized deep-inelastic lepton-nucleon scattering data, two distinct expectations have been made for ΔQ_f, the so-called SU(6) and deep-inelastic scattering (DIS) expectations [16].

The approach described above has been applied to the polarizations of different hyperons in e^+e^-, semi-inclusive DIS and pp collisions, antihyperons in semi-inclusive DIS and anti-Lambda in pp [11,12,16–21,26]. The results can be compared with data [2–7,27]. The current experimental accuracy does not allow one to distinguish between the expectations for $t_{H,f}^F$ based on the SU(6) and DIS pictures. The z dependence of the available data on Λ polarization is well described [16]. The approach is thus justified by existing data. We will use both the SU(6) and DIS pictures for our present predictions.

C. Implementation

The expression for the polarization of antihyperons $P_{\bar{H}}$ follows from the definition in Eq. (1) and the factorized cross sections (cf. Eq. (2)), and is given by

$$P_{\bar{H}}(\eta) = \frac{\int_{p_T^{\min}} dp_T \sum_{\text{abcd}} \int dx_a dx_b f_a(x_a) f_b(x_b) \frac{d\hat{\sigma}}{d\hat{t}}(ab \to cd) P_{c/ab\to cd}(x_a, y) \Delta D_c^{\bar{H}}(z)}{\int_{p_T^{\min}} dp_T \sum_{\text{abcd}} \int dx_a dx_b f_a(x_a) f_b(x_b) \frac{d\hat{\sigma}}{d\hat{t}}(ab \to cd) D_c^{\bar{H}}(z)}, \quad (14)$$

where $P_{c/ab\to cd}(x_a, y) = D_L^{\vec{a}b\to\vec{c}d}(y) \Delta f_a(x_a)/f_a(x_a)$ is the polarization of parton c before it fragments. This can be rewritten using the model to calculate $\Delta D_c^{\bar{H}}(z)$ according to the origin of $\bar{H}$ (cf. Sec. II B 3),

$$P_{\bar{H}}(\eta) = \frac{\int_{p_T^{\min}} dp_T \sum_{abcd} \sum_\alpha \int dx_a dx_b f_a(x_a) f_b(x_b) \frac{d\hat{\sigma}}{d\hat{t}}(ab \to cd) D_c^{\bar{H}(\alpha)}(z) P_{c/ab\to cd}(x_a, y) S_c^{\bar{H}(\alpha)}(z)}{\int_{p_T^{\min}} dp_T \sum_{\text{abcd}} \int dx_a dx_b f_a(x_a) f_b(x_b) \frac{d\hat{\sigma}}{d\hat{t}}(ab \to cd) D_c^{\bar{H}}(z)}, \quad (15)$$

where the summation over α concerns the four process classes from which the $\bar{H}$ originate, and $S_c^{\bar{H}(\alpha)}(z) = \Delta D_c^{\bar{H}(\alpha)}(z)/D_c^{\bar{H}(\alpha)}(z)$ denotes the spin transfer factor in the fragmentation for each of these classes (cf. Sec. II B 3).

The antihyperon polarization $P_{\bar{H}}$ can be in principle be evaluated numerically from Eq. (14). In practice, it is feasible and actually advantageous to use a Monte Carlo event generator that incorporates all hard scattering processes and uses a recursive hadronization model to evaluate $P_{\bar{H}}$ from Eq. (15). In particular, this ensures in a natural way that all subprocesses, including feed-down contributions, are taken into account. Furthermore, it facilitates comparisons of the predictions with experiment data, since event generator output can be propagated through detailed detector simulations so that, for example, the experiment kinematic acceptance for the observed $\bar{H}$ decay products can be taken into account without relying on extrapolation over unmeasured regions.

We have used the PYTHIA event generator, which incorporates the hard scattering processes and uses the Lund string fragmentation model [40], in our calculations. PYTHIA is commonly used for hadron-hadron collisions, and its output has been tested and tuned to describe a vast body of data. In particular, reasonable agreement is found for $\Lambda + \bar{\Lambda}$ production that was recently measured for transverse momenta up to 5 GeV in pp collisions at RHIC [42] when a K factor of $\sim$3 is used. For the results presented here we have used PYTHIA version 6.4 with all hard scattering processes selected and initial and final state radiation switched off. We have verified that the aforementioned K factor does not affect the polarization results.

III. ANTIHYPERON PRODUCTION

The longitudinal polarization of high p_T antihyperons produced in pp collisions is determined by the polarization of the initial partons taking part in the hard scattering, the partonic spin transfer factor, and the spin transfer in the fragmentation process. Since the up, down, and strange quark and antiquark polarizations in the polarized proton are different and the spin transfer in the fragmentation process for a given type of antihyperon is flavor dependent as well, the contributions to $\bar{H}$ production from the fragmentation of different quark flavors and gluons need to be studied. These contributions are independent of polarization and have been determined in multiparticle production data in high-energy reactions. An impressive body of data has been collected over the past decades, and the contributions can thus be considered to be known accurately and to be well modeled in Monte Carlo event generators.

As described in Sec. II C, we have used the PYTHIA generator [40] to evaluate the contributions to the production of the $\bar{\Sigma}^-$, $\bar{\Sigma}^+$, $\bar{\Xi}^0$, and $\bar{\Xi}^+$ antihyperons. The flavor compositions of these antihyperons lead us to expect a large contribution to the production of $\bar{\Sigma}^+(\bar{d}\,\bar{d}\,\bar{s})$ from $\bar{d}$ fragmentation, a large contribution to $\bar{\Sigma}^-(\bar{u}\,\bar{u}\,\bar{s})$ production from $\bar{u}$ fragmentation, and a large contribution to $\bar{\Xi}$ production from $\bar{s}$ fragmentation.

Figure 2 shows the results for the fractional contributions to $\bar{\Sigma}^-$ production from the fragmentation of antiquarks/quarks of different flavors and of gluons in pp collisions at $\sqrt{s} = 200$ GeV for hyperon transverse momenta $p_T > 8$ GeV versus pseudorapidity η. The decay contribution to $\bar{\Sigma}^-$ production is seen to be negligibly small. This is different than for $\bar{\Lambda}$ production and implies that its polarization measurement will reflect more directly the spin structure of the nucleon and the polarized fragmentation function. The results are symmetric in $\eta \leftrightarrow -\eta$, since pp collisions are considered. The $\bar{d}$-quark and s-quark fragmentation contributions originate from second or higher rank particles in the fragmentation and have similar shapes since both are sea quarks (antiquarks). The increasingly large u-quark contribution with increasing $|\eta|$ originates from valence quarks. Only the $\bar{u}$ quark and $\bar{s}$ quark give first rank fragmentation contributions.

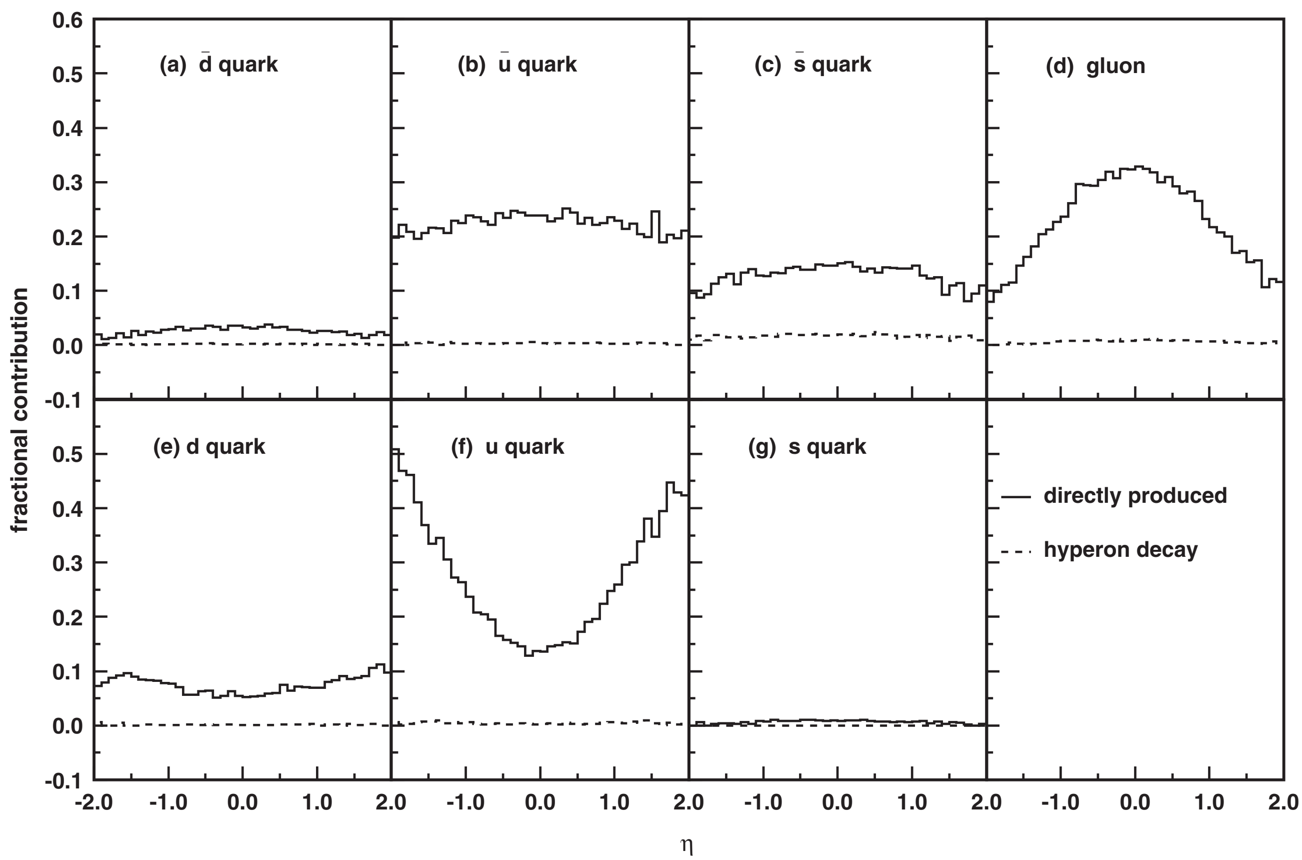

FIG. 2. Contributions to $\bar{\Sigma}^-(\bar{u}\,\bar{u}\,\bar{s})$ production with $p_T \geq 8$ GeV/c in pp collisions at $\sqrt{s} = 200$ GeV. The continuous and dashed lines are, respectively, the directly produced and decay contributions.

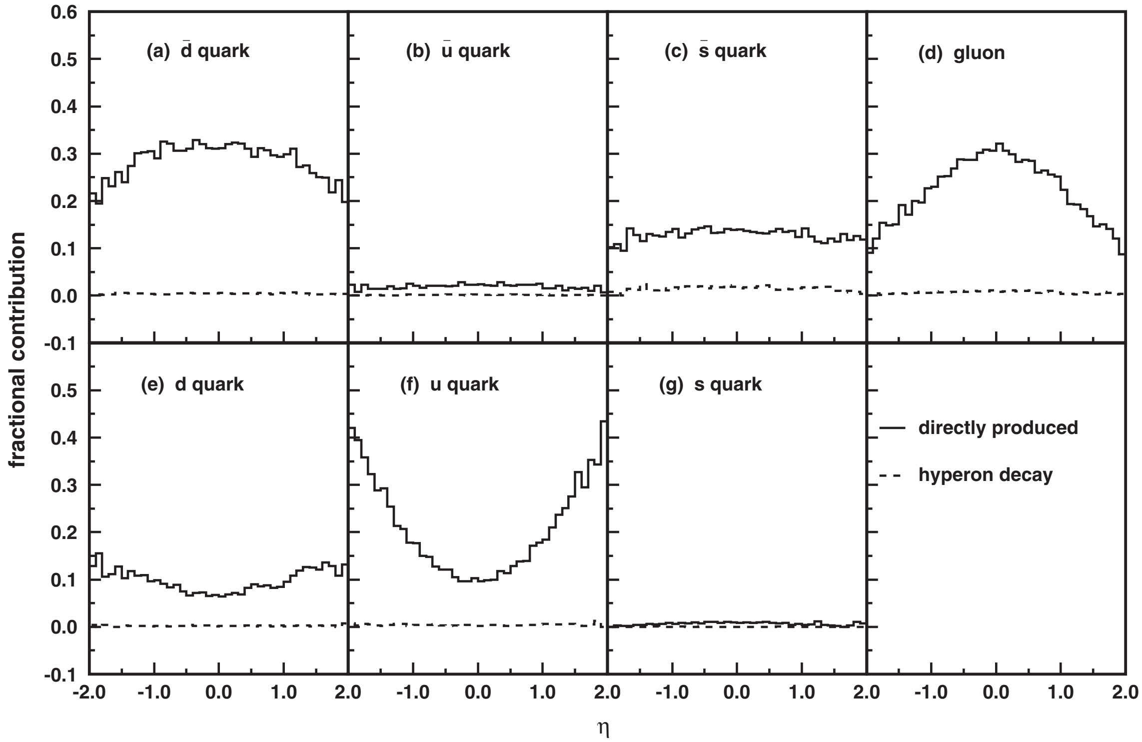

FIG. 3. Contributions to $\bar{\Sigma}^{+}(\bar{d}\,\bar{d}\,\bar{s})$ production with $p_T \geq 8$ GeV/c in pp collisions at $\sqrt{s} = 200$ GeV. The continuous and dashed lines are, respectively, the directly produced and decay contributions.

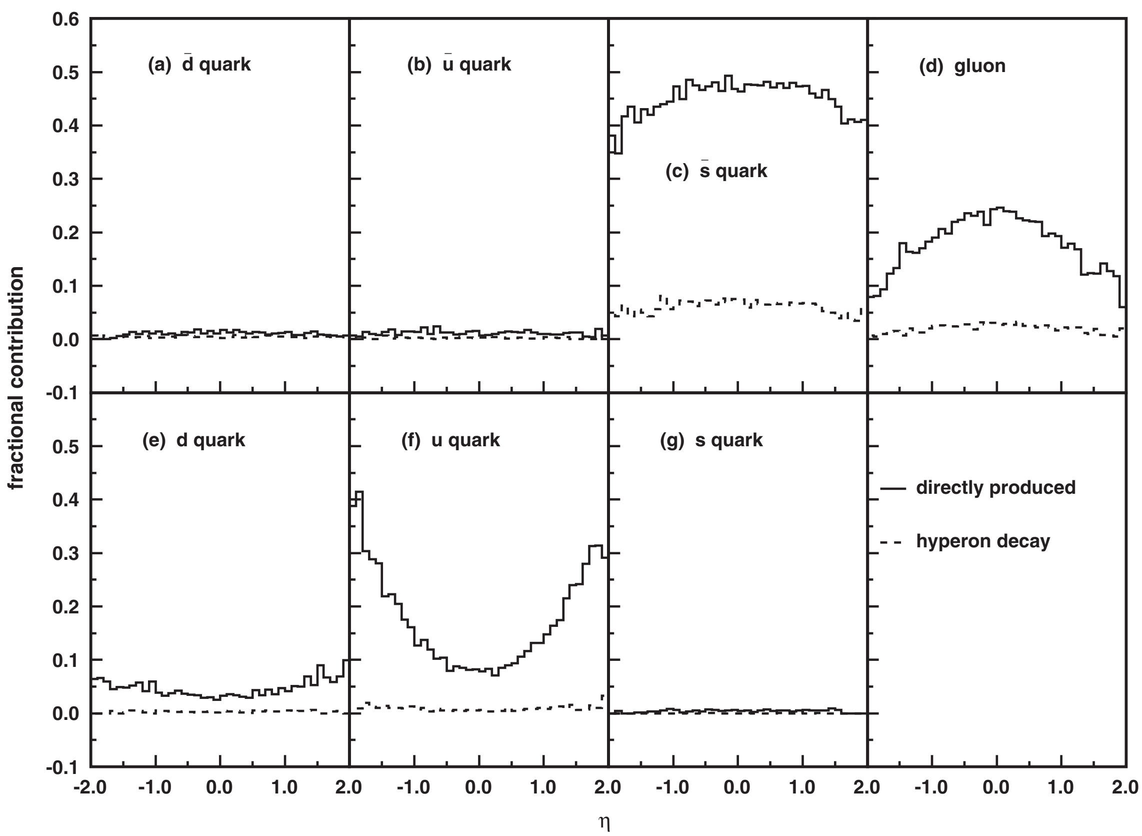

FIG. 4. Contributions to $\bar{\Xi}^{0}(\bar{u}\,\bar{s}\,\bar{s})$ production with $p_T \geq 8$ GeV/c in pp collisions at $\sqrt{s} = 200$ GeV. The continuous and dashed lines are, respectively, the directly produced and decay contributions.

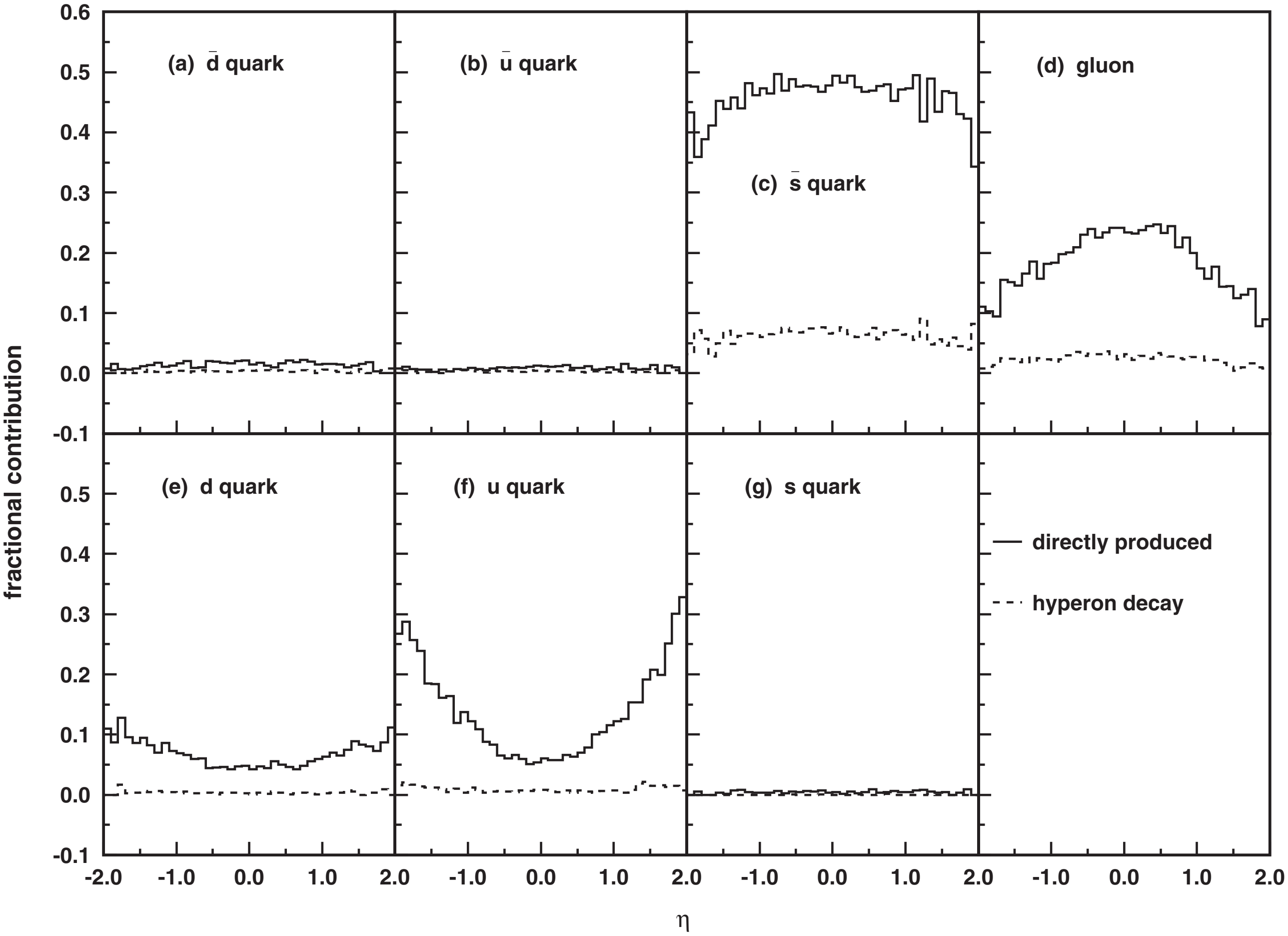

FIG. 5. Contributions to $\bar{\Xi}^+(\bar{d}\,\bar{s}\,\bar{s})$ production with $p_T \geq 8$ GeV/c in pp collisions at $\sqrt{s} = 200$ GeV. The continuous and dashed lines are, respectively, the directly produced and decay contributions.

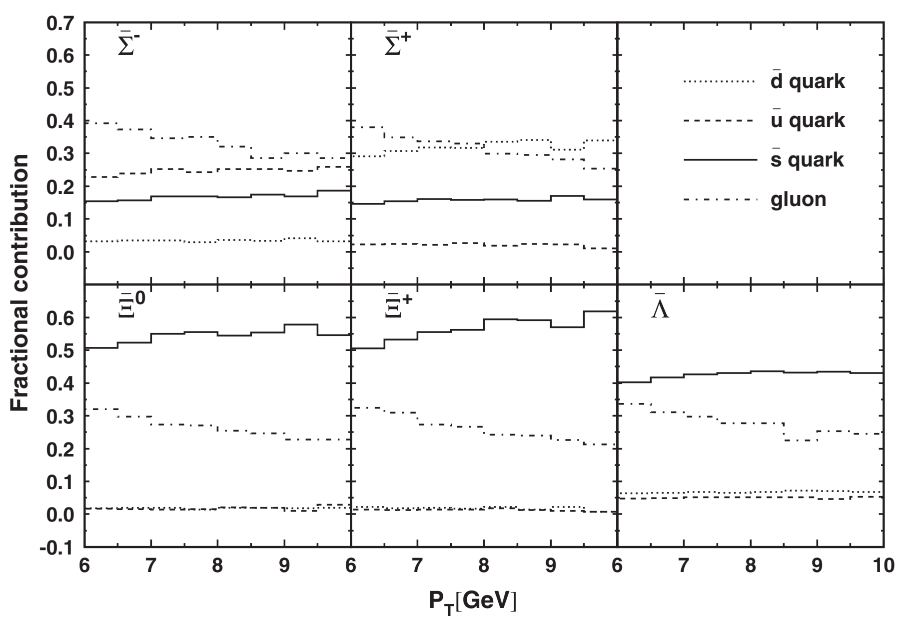

FIG. 6. Contributions to $\bar{\Sigma}^-(\bar{u}\,\bar{u}\,\bar{s})$, $\bar{\Sigma}^+(\bar{d}\,\bar{d}\,\bar{s})$, $\bar{\Xi}^0(\bar{u}\,\bar{s}\,\bar{s})$ and $\bar{\Xi}^+(\bar{d}\,\bar{s}\,\bar{s})$ production for $|\eta| < 1$ in pp collisions at $\sqrt{s} = 200$ GeV versus transverse momentum p_T.

These contributions are sizable. Most important for the production of $\bar{\Sigma}^-$ with $p_T > 8$ GeV and $|\eta| < 1$ are $\bar{u}$ and gluon fragmentation. Since the $\bar{\Sigma}^-$ spin is carried mostly by the $\bar{u}$-quark spins, this implies that the $\bar{\Sigma}^-$ polarization in singly polarized pp collisions should be sensitive to $\Delta\bar{u}(x)$, the $\bar{u}$-quark polarization distribution in the polarized proton.

The results for $\bar{\Sigma}^+$, shown in Fig. 3, are similar to those for $\bar{\Sigma}^-$ when $\bar{u}$ and $\bar{d}$ are interchanged. The small difference between the fractional contribution of the $\bar{u}$ quark to $\bar{\Sigma}^-$ production and of the $\bar{d}$ quark to $\bar{\Sigma}^+$ production reflects the asymmetry of the light sea density in the proton $\bar{d}(x) > \bar{u}(x)$, which is built into the parton distribution functions. The large $\bar{d}$-quark fragmentation contribution to $\bar{\Sigma}^+$ production and the large $\bar{d}$-quark spin contribution to the $\bar{\Sigma}^+$ spin lead us to expect that $\bar{\Sigma}^+$ polarization measurements in pp collisions are sensitive to $\Delta\bar{d}(x)$.

Figures 4 and 5 show the fractional contributions for $\bar{\Xi}^0$ and $\bar{\Xi}^+$ production, respectively. The dominant contribution originates from $\bar{s}$-quark fragmentation. It amounts to almost half the $\bar{\Xi}$ production, and is larger than the $\bar{d}$-quark fragmentation contribution to $\bar{\Sigma}^+$ production and the $\bar{u}$-quark fragmentation contribution to $\bar{\Sigma}^-$ production. This results from strange suppression, which reduces the relative contributions from $\bar{u}$ and $\bar{d}$-quark fragmentation to $\bar{\Xi}$ production. We thus expect that $\bar{\Xi}$ polarization measurements are sensitive to $\Delta\bar{s}(x)$ in the nucleon. They are thus complementary to polarization measurements of the $\bar{\Lambda}$ [26], which has a larger production cross section but also larger decay contributions.

In Fig. 6, we show the p_T dependence of the fractional fragmentation contributions for the midrapidity region $|\eta| < 1$, for the $\bar{\Sigma}^-$, $\bar{\Sigma}^+$, $\bar{\Xi}^0$, $\bar{\Xi}^+$, as well as the $\bar{\Lambda}$. The antiquark contributions generally increase with increasing p_T, and the gluon contributions decrease.

IV. RESULTS AND DISCUSSION

We have evaluated $P_{\bar{H}}$ for the $\bar{\Sigma}^-$, $\bar{\Sigma}^+$, $\bar{\Xi}^0$, and $\bar{\Xi}^+$ antihyperons as a function of η for $p_T \geq 8$ GeV and $\sqrt{s} = 200$ GeV using different parametrizations for the polarized parton distributions and using the SU(6) and DIS pictures for the spin transfer factors $t^F_{H,q}$ in the fragmentation. In all cases, the unpolarized parton distributions of Ref. [43] were used. The results using the polarized parton distributions of Ref. [32] are shown in Fig. 7, together with our previous results for $P_{\bar{\Lambda}}$ [26]. The main characteristics are

(i) the size of the polarization increases in the forward direction with respect to the polarized proton beam and can be as large as 10% ($\bar{\Xi}^0$, $\bar{\Xi}^+$) at $\eta = 2$,

(ii) the differences between the $\bar{H}$ polarizations obtained for different parametrizations of the polarized parton distribution functions are generally larger than the differences between the results for different models for the spin transfer in fragmentation,

(iii) the size of the polarizations for the $\bar{\Sigma}^-$ and $\bar{\Sigma}^+$ hyperons is smaller than for the $\bar{\Lambda}$ and $\bar{\Xi}$ hyperons because of the lower fractional contributions from $\bar{u}$ and $\bar{d}$ fragmentation to $\bar{\Sigma}^-$ and $\bar{\Sigma}^+$ production

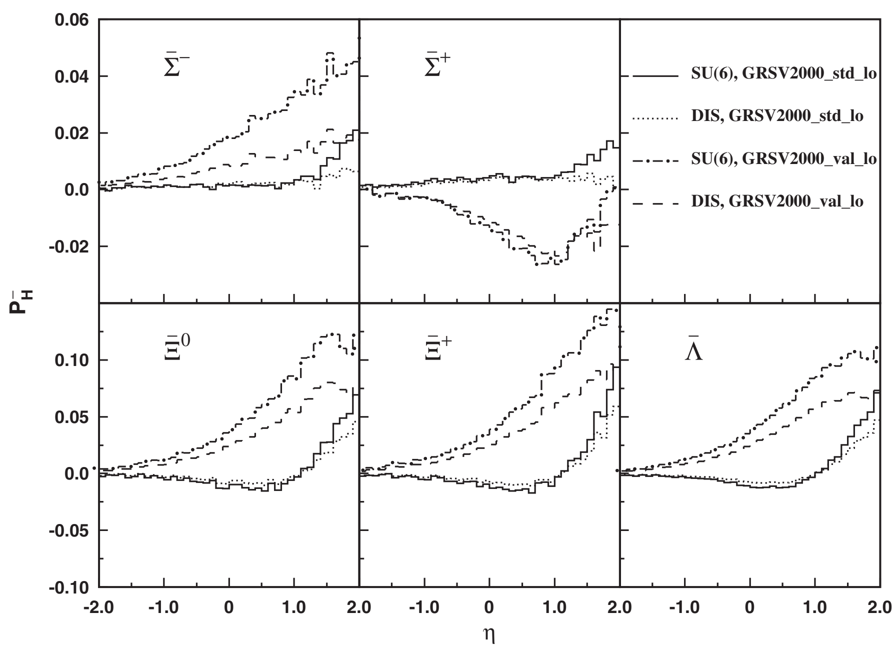

FIG. 7. Longitudinal polarization for antihyperons with transverse momentum $p_T \geq 8$ GeV/c in pp collisions at $\sqrt{s} = 200$ GeV with one longitudinally polarized beam versus pseudorapidity η. Positive η is taken along the direction of the polarized beam.

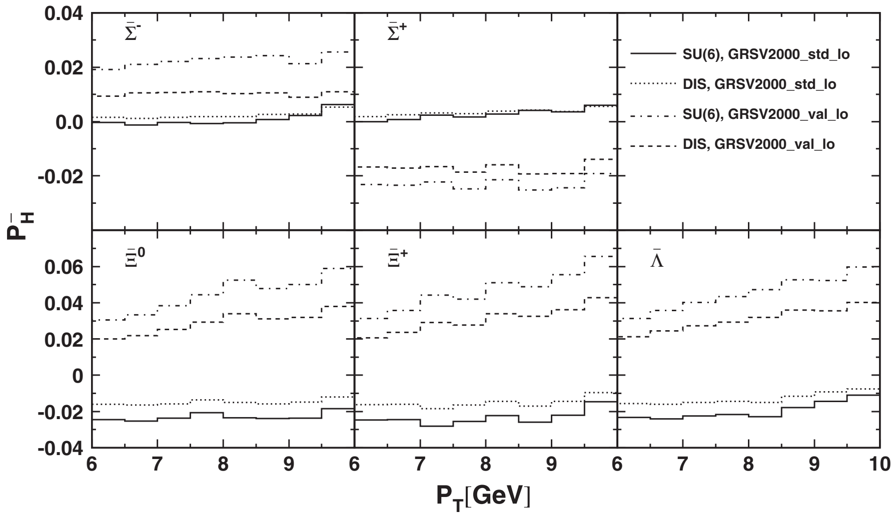

FIG. 8. Longitudinal polarization for antihyperons with pseudorapidity $0 < \eta < 1$ in pp collisions at $\sqrt{s} = 200$ GeV with one longitudinally polarized beam versus transverse momentum p_T. Positive η is taken along the direction of the polarized beam.

than from $\bar{s}$ fragmentation to the $\bar{\Lambda}$ and $\bar{\Xi}$ production,

(iv) the results for $\bar{\Sigma}^-$ and $\bar{\Sigma}^+$ for the GRSV2000 valence distributions differ in sign because of the sign difference in $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$, and in size and shape because of flavor-symmetry breaking in the unpolarized and this polarized parton distribution scenario,

(v) the $\bar{\Xi}^0$ and $\bar{\Xi}^+$ polarizations are similar to each other because of the dominance of $\bar{s}$ fragmentation; they are somewhat larger than the $\bar{\Lambda}$ polarization because of the smaller decay contributions and their sensitivity to $\Delta\bar{s}$ is thus more direct.

Figure 8 shows the polarizations in the pseudorapidity range $0 < \eta < 1$ versus transverse momentum p_T. The polarizations are sensitive mostly to the polarized antiquark distributions for momentum fractions $0.05 < x < 0.25$ and the p_T dependences are consequently not very strong. Only a modest variation is expected also with center-of-mass energy. To illustrate this, we have repeated the calculations for $\sqrt{s} = 500$ GeV. Figure 9 shows the η dependence for $p_T > 10$ GeV. Apart from differences ex-

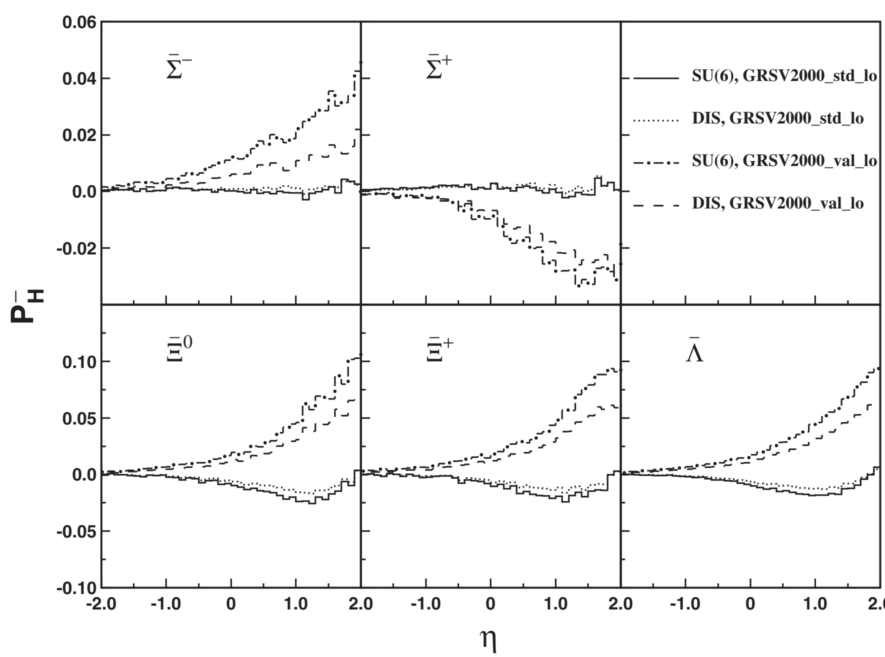

FIG. 9. Longitudinal polarization for antihyperons with $p_T > 10$ GeV as a function of the pseudorapidity η in pp collisions at $\sqrt{s} = 500$ GeV with one longitudinally polarized beam. Positive η is taken along the direction of the polarized beam.

pected from phase space, the results are seen to be very similar to those in Fig. 7.

Gluon fragmentation is seen to contribute sizably to the production of antihyperons in the central rapidity range in Figs. 2–6. The fragmentation of gluons is less well known than that of quarks even in the unpolarized case and also the polarization of gluons in the colliding polarized protons cannot be determined precisely from current data. In the estimates, as in earlier calculations [11,12,16–21,26], we have taken into account the spin transfer in the hard scattering of gluons, and have neglected the spin transfer in the fragmentation of gluons into antihyperons. This assumption is consistent with the model used for the polarized fragmentation functions. Data with improved precision on the production cross sections and on gluon polarization would provide important constraints. In particular, we expect that our results are largely unaffected if the gluon spin contribution to the proton spin is found to be small. Current data [44] excludes the large values that were proposed originally to explain the quark spin contribution to the proton spin [45].

Last, we have estimated the precision with which $\bar{H}$ polarization measurements could be made at RHIC [28]. For an analyzed integrated luminosity of $\mathcal{L} \simeq 300\ \mathrm{pb}^{-1}$ and a proton beam polarization of $P \simeq 70\%$, we anticipate that, e.g., $P_{\bar{\Xi}}$ could be measured to within ~ 0.02 uncertainty. Measurements of $\bar{H}$ polarization at RHIC are thus worthwhile in view of the presently limited knowledge of $\Delta\bar{q}(x)$ in the nucleon, as evidenced, in particular, by the large differences between the parametrization sets of Ref. [32].

V. SUMMARY

In summary, we have evaluated the longitudinal polarizations of the $\bar{\Sigma}^-$, $\bar{\Sigma}^+$, $\bar{\Xi}^0$, and $\bar{\Xi}^+$ antihyperons in highly energetic collisions of longitudinally polarized proton beams. The results show sensitivity to the antiquark polarizations in the nucleon sea. In particular, the $\bar{\Sigma}^-$ and $\bar{\Sigma}^+$ polarizations are sensitive to the light sea quark polarizations, $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$. The $\bar{\Xi}^0$ and $\bar{\Xi}^+$ polarizations are sensitive to strange antiquark polarization $\Delta\bar{s}(x)$. Precision measurements at the RHIC polarized pp collider should be able to provide new insights in the sea quark polarizations in the nucleon.

ACKNOWLEDGMENTS

This work was supported in part by the National Science Foundation of China (NSFC) under Grant Nos. 10525523 and 10405016, and by the United States Department of Energy under Contract No. DE-AC02-05CH11231, Office of Nuclear Physics, and by the Department of Science and Technology of Shandong Province of China under Contract No. 2006GG2210013. .

[1] T. D. Lee and C. N. Yang, Phys. Rev. **108**, 1645 (1957); T. D. Lee, J. Steinberger, G. Feinberg, P. K. Kabir, and C. N. Yang, Phys. Rev. **106**, 1367 (1957).
[2] D. Buskulic *et al.* (ALEPH Collaboration), Phys. Lett. B **374**, 319 (1996).
[3] K. Ackerstaff *et al.* (OPAL Collaboration), Eur. Phys. J. C **2**, 49 (1998).
[4] P. Astier *et al.* (NOMAD Collaboration), Nucl. Phys. **B588**, 3 (2000); **B605**, 3 (2001).
[5] A. Airapetian *et al.* (HERMES Collaboration), Phys. Rev. D **64**, 112005 (2001); **74**, 072004 (2006).
[6] M. R. Adams *et al.* (E665 Collaboration), Eur. Phys. J. C **17**, 263 (2000).
[7] M. G. Sapozhnikov (COMPASS Collaboration), arXiv: hep-ex/0503009; arXiv:hep-ex/0602002; also V. Yu. Alexakhin (COMPASS Collaboration), arXiv:hep-ex/0502014.
[8] A. Lesnik *et al.* Phys. Rev. Lett. **35**, 770 (1975); G. Bunce *et al.*, Phys. Rev. Lett. **36**, 1113 (1976); K. Heller *et al.*, Phys. Rev. Lett. **41**, 607 (1978); For a review, see e.g., A. Bravar, in *Proc. of the 13th International Symposium on High Energy Spin Physics, Protvino, Russia, September 1998*, edited by N. E. Tyurin *et al.* (World Scientific, Singapore, 1999), p. 167.
[9] See e.g., B. Andersson, G. Gustafson, and G. Ingelman, Phys. Lett. **85B**, 417 (1979); T. A. DeGrand and H. I. Miettinen, Phys. Rev. D **24**, 2419 (1981); J. Soffer and N. Törnqvist, Phys. Rev. Lett. **68**, 907 (1992); Z. T. Liang and C. Boros, Phys. Rev. Lett. **79**, 3608 (1997); Phys. Rev. D **61**, 117503 (2000); H. Dong and Z. T. Liang, Phys. Rev. D **70**, 014019 (2004), and references therein.
[10] M. Burkardt and R. L. Jaffe, Phys. Rev. Lett. **70**, 2537 (1993); R. L. Jaffe, Phys. Rev. D **54**, R6581 (1996).
[11] G. Gustafson and J. Häkkinen, Phys. Lett. B **303**, 350 (1993).
[12] C. Boros and Z. T. Liang, Phys. Rev. D **57**, 4491 (1998).
[13] A. Kotzinian, A. Bravar, and D. von Harrach, Eur. Phys. J. C **2**, 329 (1998).
[14] D. de Florian, M. Stratmann, and W. Vogelsang, Phys. Rev. Lett. **81**, 530 (1998); Phys. Rev. D **57**, 5811 (1998).
[15] B. Q. Ma and J. Soffer, Phys. Rev. Lett. **82**, 2250 (1999).
[16] C. X. Liu and Z. T. Liang, Phys. Rev. D **62**, 094001 (2000).
[17] C. X. Liu, Q. H. Xu, and Z. T. Liang, Phys. Rev. D **64**, 073004 (2001).
[18] Q. H. Xu, C. X. Liu, and Z. T. Liang, Phys. Rev. D **65**, 114008 (2002).
[19] Z. T. Liang and C. X. Liu, Phys. Rev. D **66**, 057302 (2002).
[20] Q. H. Xu and Z. T. Liang, Phys. Rev. D **70**, 034015 (2004).

[21] H. Dong, J. Zhou, and Z. T. Liang, Phys. Rev. D **72**, 033006 (2005).

[22] C. Boros, J. T. Londergan, and A. W. Thomas, Phys. Rev. D **62**, 014021 (2000).

[23] B. Q. Ma, I. Schmidt, and J. J. Yang, Phys. Rev. D **61**, 034017 (2000); **63**, 037501 (2001); B. Q. Ma, I. Schmidt, J. Soffer, and J. J. Yang, Phys. Rev. D **62**, 114009 (2000); Eur. Phys. J. C **16**, 657 (2000); Nucl. Phys. **A703**, 346 (2002).

[24] M. Anselmino, M. Boglione, and F. Murgia, Phys. Lett. B **481**, 253 (2000).

[25] J. R. Ellis, A. Kotzinian, and D. V. Naumov, Eur. Phys. J. C **25**, 603 (2002); J. Ellis, A. Kotzinian, D. Naumov, and M. Sapozhnikov, Eur. Phys. J. C **52**, 283 (2007).

[26] Q. H. Xu, Z. T. Liang, and E. Sichtermann, Phys. Rev. D **73**, 077503 (2006).

[27] Q. H. Xu (STAR Collaboration), AIP Conf. Proc. **842**, 71 (2006); AIP Conf. Proc. **915**, 428 (2007).

[28] G. Bunce, N. Saito, J. Soffer, and W. Vogelsang, Annu. Rev. Nucl. Part. Sci. **50**, 525 (2000).

[29] R. Gastmans and T. T. Wu, *The Ubiquitous Photon* (Clarendon Press, Oxford, 1990).

[30] J. Babcock, E. Monsay, and D. W. Sivers, Phys. Rev. Lett. **40**, 1161 (1978); Phys. Rev. D **19**, 1483 (1979).

[31] B. Jäger, A. Schäfer, M. Stratmann, and W. Vogelsang, Phys. Rev. D **67**, 054005 (2003).

[32] M. Glück, E. Reya, M. Stratmann, and W. Vogelsang, Phys. Rev. D **63**, 094005 (2001); **53**, 4775 (1996).

[33] J. Blümlein and H. Böttcher, Nucl. Phys. **B636**, 225 (2002).

[34] E. Leader, A. V. Sidorov, and D. B. Stramenov, Phys. Rev. D **73**, 034023 (2006); **75**, 074027 (2007).

[35] T. Gehrmann and W. J. Stirling, Phys. Rev. D **53**, 6100 (1996).

[36] M. Hirai *et al.* (Asymmetry Analysis Collaboration), Phys. Rev. D **69**, 054021 (2004); **74**, 014015 (2006).

[37] D. De Florian and R. Sassot, Phys. Rev. D **62**, 094025 (2000).

[38] D. De Florian, G. A. Navarro, and R. Sassot, Phys. Rev. D **71**, 094018 (2005).

[39] V. N. Gribov and L. N. Lipatov, Phys. Lett. **37B**, 78 (1971); Yad. Fiz. **15**, 1218 (1972) [Sov. J. Nucl. Phys. **15**, 675 (1972)].

[40] T. Sjöstrand, S. Mrenna, and P. Skands, J. High Energy Phys. 05 (2006) 026; B. Andersson, G. Gustafson, G. Ingelman, and T. Sjöstrand, Phys. Rep. **97**, 31 (1983).

[41] R. D. Field and R. P. Feynman, Nucl. Phys. **B136**, 1 (1978).

[42] B. I. Abelev *et al.* (STAR Collaboration), Phys. Rev. C **75**, 064901 (2007).

[43] M. Glück, E. Reya, and A. Vogt, Eur. Phys. J. C **5**, 461 (1998).

[44] S. Adler *et al.*(PHENIX Collaboration), Phys. Rev. Lett. **93**, 202002 (2004); Phys. Rev. D **73**, 091102 (2006); A. Adare *et al.* (PHENIX Collaboration), Phys. Rev. D **76**, 051106 (2007); B. I. Abelev *et al.* (STAR Collaboration), Phys. Rev. Lett. **97**, 252001 (2006); Phys. Rev. Lett. **100**, 232003 (2008); E. S. Ageev *et al.* (COMPASS Collaboration), Phys. Lett. B **633**, 25 (2006); **647**, 8 (2007); B. Adeva *et al.* (Spin Muon Collaboration (SMC)), Phys. Rev. D **70**, 012002 (2004); A. Airapetian *et al.* (HERMES Collaboration), Phys. Rev. Lett. **84**, 2584 (2000).

[45] G. Altarelli and G. G. Ross, Phys. Lett. B **212**, 391 (1988); R. D. Carlitz, J. C. Collins, and A. H. Mueller, Phys. Lett. B **214**, 229 (1988).