Anti-Lambda polarization in high energy pp collisions with polarized beams

Qing-hua Xu,[1,2] Zuo-tang Liang,[1,2] and Ernst Sichtermann[2]

[1]*Department of Physics, Shandong University, Jinan, Shandong 250100, China*

[2]*Nuclear Science Division, MS 70R0319, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

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We study the polarization of the anti-Lambda particle in polarized high energy pp collisions at large transverse momenta. The anti-Lambda polarization is found to be sensitive to the polarization of the antistrange sea of the nucleon. We make predictions using different parametrizations of the polarized quark distribution functions. The results show that the measurement of longitudinal anti-Lambda polarization can distinguish different parametrizations, and that similar measurements in the transversely polarized case can give some insights into the transversity distribution of the antistrange sea of nucleon.

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The polarizations of hyperons, in particular, the Lambda (Λ), have been widely used to study various aspects of spin effects in high energy reactions for their self spin-analyzing parity violating decay [1]. Many studies, both experimentally [2–7] and theoretically [8–20] have been made recently, in particular, on the spin transfer in high energy fragmentation processes. Here, it is of particular interest to know whether the SU(6) wave-function or the results drawn from polarized deep-inelastic lepton-nucleon scattering (DIS) should be used in connecting the spin of the fragmenting quark and that of the produced hadrons. In addition such studies can give insight into the spin structure of the nucleon. For example, the transversity distribution can be studied by measuring the polarization of the Sigma (Σ^+) in $pp \to \Sigma^+ X$ with transversely polarized beams and the gluon helicity distributions in $pp \to \gamma\Sigma^+ X$ with longitudinally polarized beams [17].

Presently, most of our knowledge on the flavor decomposition of the proton spin originates from deep-inelastic measurements. Polarized inclusive deep-inelastic scattering data from CERN, SLAC, DESY, and JLAB [21–24], combined with hyperon β decay measurements, indicate that the strange sea in the nucleon, $\Delta s + \Delta\bar{s}$, is negatively polarized. Recent semi-inclusive deep-inelastic scattering data [25] may indicate a different outcome. These data do not rely on hyperon decay measurements, but cover a smaller kinematic range than the inclusive data and some analysis aspects have come under discussion [26]. Further similar measurements are underway or planned [27,28]. Data from elastic neutrino scattering [29] lack the precision to distinguish, but better measurements have been proposed [30]. Other measurements are called for.

In this note, we evaluate the polarization of inclusive anti-Lambda's in polarized pp collisions at large transverse momenta (p_T). We study the dependence of the results on the polarized quark distributions and show that the anti-Lambda polarization is quite sensitive to the anti-strange sea polarization ($\Delta\bar{s}$) in the nucleon in regions accessible to experiments.

We consider the inclusive production of anti-Lambda ($\bar{\Lambda}$) particles with high transverse momenta p_T in pp collisions with one beam longitudinally polarized. The $\bar{\Lambda}$ polarization is defined as,

$$P_{\bar{\Lambda}} \equiv \frac{d\sigma(p_+ p \to \bar{\Lambda}_+ X) - d\sigma(p_+ p \to \bar{\Lambda}_- X)}{d\sigma(p_+ p \to \bar{\Lambda}_+ X) + d\sigma(p_+ p \to \bar{\Lambda}_- X)} = \frac{d\Delta\sigma^{\bar{\Lambda}}}{d\eta} \Big/ \frac{d\sigma^{\bar{\Lambda}}}{d\eta}, \quad (1)$$

where η is the pseudorapidity of the $\bar{\Lambda}$, and $\Delta\sigma$ and σ are the polarized and unpolarized inclusive production cross sections; the subscript $+$ or $-$ denote the helicity of the particle. We assume that p_T is high enough so that the factorization theorem is expected to hold and the produced $\bar{\Lambda}$'s are the fragmentation products of high p_T partons in $2 \to 2$ hard scattering ($ab \to cd$) with one initial parton polarized. Hence,

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

where the sum concerns all possible subprocesses; the transverse momenta p_T of the $\bar{\Lambda}$ is integrated above $p_T^{\min}$; $\Delta f_a(x_a)$ and $f_b(x_b)$ are the longitudinally polarized and unpolarized parton distribution functions in the proton (whose scale dependence we omit for notational clarity); x_a and x_b are the momentum fractions carried by partons a and b; $D^{\vec{a}b\to\vec{c}d}(y) \equiv d\Delta\hat{\sigma}/d\hat{\sigma}$ is the partonic spin transfer factor in the elementary hard process $\vec{a}b \to \vec{c}d$; $\Delta D_c^{\bar{\Lambda}}(z)$ is the polarized fragmentation function defined by,

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

in which the arguments $+$ and $-$ denote that the produced $\bar{\Lambda}$ has the same or opposite helicity as the fragmenting parton c. Experimentally, such spin-dependent fragmentation functions can be studied in e^+e^--annihilation, polarized deeply inelastic scattering and high p_T hadron production in polarized pp collisions by measuring hyperon polarization in the final states [8–20]. This is because in all these cases, the polarization of quarks or antiquarks before fragmentation can be calculated using the standard model for electro-weak interaction or pQCD together with the empirical knowledge for polarized parton distributions [31]. The partonic spin transfer factor $D^{\vec{a}b\to\vec{c}d}$ is calculable in pQCD and turns out to be a function of only $y \equiv p_b \cdot (p_a - p_c)/p_a \cdot p_b$, where p_{a-d} are the parton momenta (see e.g. [15]). The unpolarized cross section $d\sigma/d\eta$ is described by an expression similar to that in Eq. (2) and can be evaluated from parametrizations of the unpolarized parton distribution and fragmentation functions.

The unknowns in Eq. (2) are in principle the polarized fragmentation functions $\Delta D_c^{\bar{\Lambda}}(z)$ and the polarized parton distributions $\Delta f_a(x_a)$. With external input for one of them, the other can be studied via the measurements of $P_{\bar{\Lambda}}$.

Studies of the polarized fragmentation functions to hyperons (H) and antihyperons ($\bar{H}$), $\Delta D_c^H(z)$ and $\Delta D_c^{\bar{H}}(z)$, have been made over the past decade [8–20]. In particular, the polarized fragmentation functions have been calculated [8,10,14–18], for directly produced (anti-)hyperons that contain the fragmenting parton c using different models for the spin transfer factor $t^F_{H,c}$ ($t^F_{\bar{H},c}$) from the parton c to the hyperon H (or $\bar{H}$). Although data are still too scarce to adequately constrain the models, the z-dependence of $\Delta D_c^{\bar{H}}(z)$ appears to be determined by the interplay of the different contributions to the unpolarized fragmentation functions, as seen from the detailed analysis in Ref. [18]. The various models differ mainly by a constant factor. Besides, a large fraction of high p_T hyperons, in particular Σ^+, in pp collisions are the leading particles in the high p_T jets. They have a large probability to be the first rank hadrons in the fragmentation of the hard scattered quarks [15]. This further reduces the influence of the different models for $\Delta D_c^H(z)$ on the hyperon polarization. Measurements of hyperon polarization can thus give insight into the polarized parton distributions.

The production of high p_T Λ's in pp collisions is more involved than Σ^+ production because it is dominated by u-quark fragmentation, and the u-quarks contribute at best only a small fraction of the Λ spin. In addition the contribution from decays of heavier hyperons to Λ's is sizable. The resulting Λ polarization is expected to be small and its evaluation is prone to many uncertainties [15].

The situation for the $\bar{\Lambda}$ is different because antiquark fragmentation dominates its production. The contributions from $\bar{u}$, $\bar{d}$ and $\bar{s}$ to the production of jets are expected to be approximately equal. Since there is a strange suppression factor [32] of $\lambda \approx 0.3$ for $\bar{\Lambda}$ production in $\bar{u}$ or $\bar{d}$ fragmentation compared to $\bar{s}$, we expect that $\bar{s}$ fragmentation gives the most important contribution to $\bar{\Lambda}$ production in $pp \to \bar{\Lambda}X$. In this case, we should expect that many of the $\bar{\Lambda}$'s at high p_T are directly produced and contain the hard scattered $\bar{s}$.

We have made estimates using the Monte-Carlo event generator PYTHIA6.205 [33] in its default tune. Figure 1 shows the expected fractional contributions to $\bar{\Lambda}$ with $p_T \geq 8$ GeV as a function of the pseudorapidity η in pp collisions at $\sqrt{s} = 200$ GeV. In Fig. 2, we show the fractional contributions in the rapidity region $|\eta| < 1$ as a function of p_T. We see that, in particular, in the region $p_T \geq 8$ GeV and $|\eta| < 1$, $\bar{s}$ fragmentation indeed provides the largest contribution to the $\bar{\Lambda}$ production, whereas the fragmentation contributions from $\bar{u}$ and $\bar{d}$ are very small. In the polarized case, we take the fact that the spin transfer factor from $\bar{s}$ to $\bar{\Lambda}$ is much larger than that from $\bar{u}$ or $\bar{d}$ into account and expect an even stronger $\bar{s}$ dominance in the $\bar{\Lambda}$ polarization. Therefore, we expect that in $\vec{p}p \to \bar{\Lambda}X$, the polarization of the $\bar{\Lambda}$ should be sensitive to the antistrange sea polarization and that the size should be somewhat larger than that of the Λ.

Using different sets of parametrizations for the polarized parton distributions [31] and the parameterization for the unpolarized parton distributions in Ref. [34], we evaluated $P_{\bar{\Lambda}}$ as a function of η for $p_T \geq 8$ GeV using Eqs. (1)–(3). As in [10,14–18], we used the SU(6) and DIS pictures for the spin transfer factor $t^F_{\bar{H},c}$. The decay contributions from heavier antihyperons are taken into account in the same

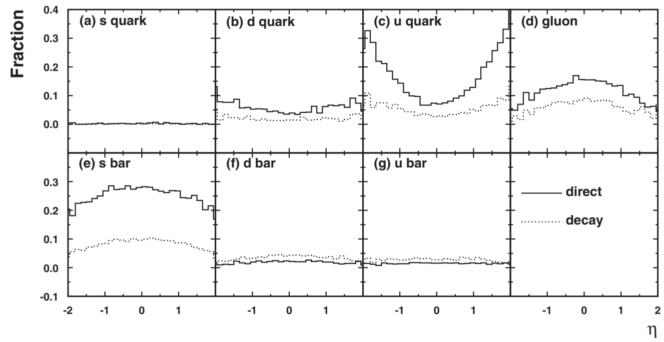

FIG. 1. Contributions to $\bar{\Lambda}$ production at $p_T \geq 8$ GeV/c in pp collisions at $\sqrt{s} = 200$ GeV. The solid and dashed lines are, respectively, the directly produced and decay contributions.

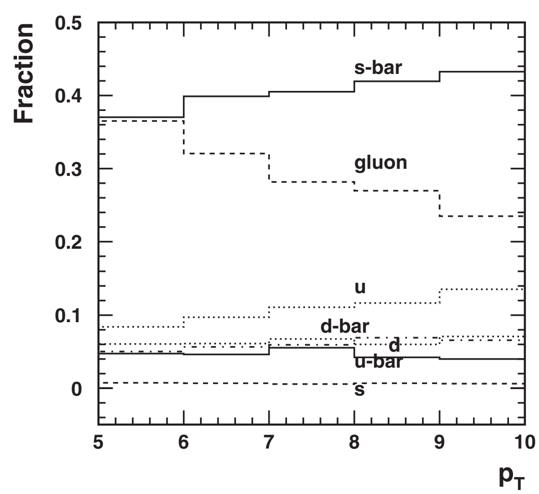

FIG. 2. Contributions to $\bar{\Lambda}$ production for $|\eta| < 1$ in pp collisions at $\sqrt{s} = 200$ GeV versus transverse momentum p_T.

way as in [10,14–18]. The second rank antihyperons and those from gluon fragmentation are taken as unpolarized. The different contributions to the $\bar{\Lambda}$ production are calculated using PYTHIA6.205. The factorization scale is taken as p_T.

After the calculations, we found out that $|P_{\bar{\Lambda}}|$ is indeed somewhat larger than $|P_{\Lambda}|$ obtained in [15] using the same sets of polarized parton distribution functions. The difference between the results obtained using different spin transfer models is relatively small whereas the difference between the results obtained using different parametrizations of the polarized parton distributions can be quite large. The latter difference originates predominantly from the differences in the parametrizations for $\Delta\bar{s}$ in the x region $0.05 < x < 0.25$ from which most $\bar{\Lambda}$'s with $p_T > 8$ GeV$/c$ originate. As examples, we show the results obtained using the GRSV "standard" and "valence" sets of parametrization of the polarized parton distributions [31] in Fig. 3. The influence from the differences in $\Delta\bar{u}$ or $\Delta\bar{d}$ is very small since aforementioned fragmentation and spin contributions are small. We have cross-checked that $P_{\bar{\Lambda}}$ evaluated with $\Delta\bar{u} = \Delta\bar{d} = 0$ shows no visible difference from the results in Fig. 3. In view of the current status of our knowledge on $\Delta\bar{s}(x)$ in nucleon, in particular, the large difference between the different sets of parametrizations [31], the measurements of $\bar{\Lambda}$ polarization are valuable.

In the calculations, we chose $p_T \geq 8$ GeV so that the factorization theorem and pQCD calculations are expected to apply. We expect that the qualitative features of the results are similar at lower p_T. We used the spin transfer factors for the hard elementary processes to the leading order (LO) in pQCD. This is to be consistent with the fragmentation functions where the empirical knowledge is used. Clearly, NLO corrections can and should be studied, in particular, in view of the results for A_{LL} as discussed e.g. in [35]. Such a study can be performed if we know the polarized fragmentation functions to this order. The fragmentation functions have to be extracted from experiments and the presently available data in this connection is still too scare for such a study.

At RHIC [36], we expect 100 K $\bar{\Lambda}$'s with $p_T > 8$ GeV/c and $-1 < \eta < 1$, corresponding to a statistical uncertainty of 0.01 in the extracted asymmetry, for an integrated luminosity of 100 pb^{-1} and a beam polarization of 50%. RHIC should thus have a good chance to distinguish between the different quark polarization parametrizations.

We can extend the calculations to the transversely polarized case, where we have,

$$\frac{d\delta\sigma^{\bar{\Lambda}}}{d\eta} = \int_{p_T^{\min}} dp_T \sum_{abcd} \int dx_a dx_b \delta f_a(x_a) f_b(x_b) \delta D_c^{\bar{\Lambda}}(z) \times D_T^{a^\dagger b \to c^\dagger d}(y) \frac{d\hat{\sigma}}{d\hat{t}}(ab \to cd) \tag{4}$$

Here, $\delta D_c^H(z)$ and $\delta q(x)$ are the polarized fragmentation functions in the transversely polarized case and transversity distributions of the quarks or antiquarks. They can be studied experimentally e.g. in semi-inclusive deep-inelastic lepton-nucleon scattering with transversely polarized nucleon or high-p_T hyperon production in transversely polarized pp collisions by measuring the hyperon polarization in the final state. The partonic spin transfer factor for the elementary hard scattering process is replaced by $D_T^{a^\dagger b \to c^\dagger d}(y)$ for transverse polarization, which is also calculable from pQCD for the elementary hard scattering processes (see e.g. [37]).

As in the longitudinally polarized case, the $\bar{\Lambda}$ polarization in the transversely polarized pp collision is also dominated by the $\bar{s}$ fragmentation and spin contributions. Therefore $P_{\bar{\Lambda},T}$ should be sensitive to $\delta\bar{s}(x)$. We made an estimate of $P_{\bar{\Lambda},T}$ assuming $\delta D_c^H(z) = \Delta D_c^H(z)$ and

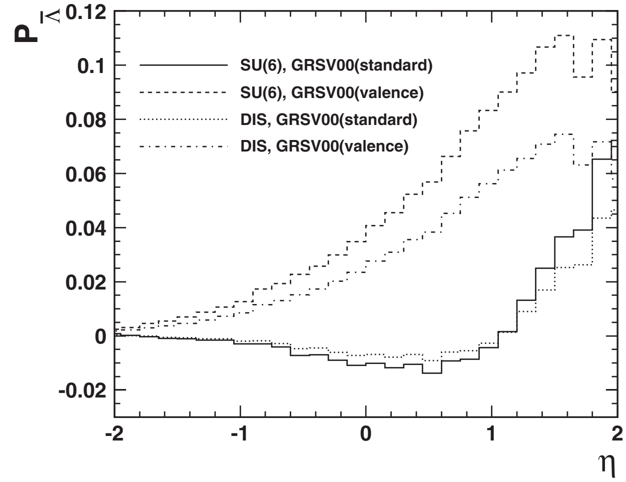

FIG. 3. Longitudinal $\bar{\Lambda}$ polarization for transverse momentum $p_T \geq 8$ GeV$/c$ in pp collisions at $\sqrt{s} = 200$ with one longitudinally polarized beam versus pseudorapidity η of the $\bar{\Lambda}$. Positive η is taken along the polarized beam direction.

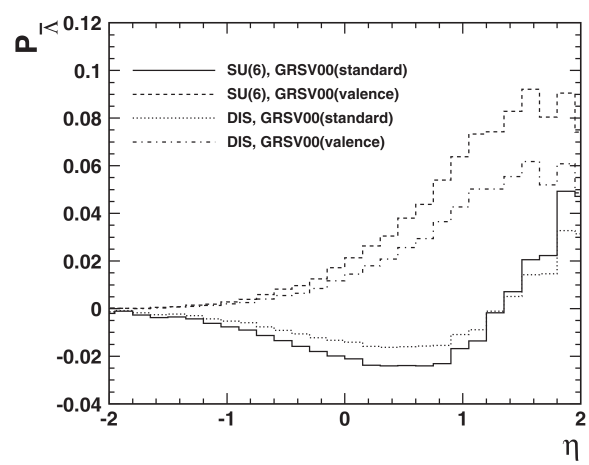

FIG. 4. Transverse $\bar{\Lambda}$ polarization for transverse momentum $p_T \geq 8$ GeV$/c$ in pp collisions at $\sqrt{s} = 200$ with one transversely polarized beam versus pseudorapidity η of the $\bar{\Lambda}$. Positive η is taken along the polarized beam direction.

$\delta q(x) = \Delta q(x)$. The results are given in Fig. 4. The differences between the results in Fig. 3 and 4 originate from the differences between $D^{\vec{a}b\to\vec{c}d}(y)$ and $D_T^{a^\uparrow b\to c^\uparrow d}(y)$.

In summary, we studied anti-Lambda ($\bar{\Lambda}$) polarization ($P_{\bar{\Lambda}}$) in polarized high energy pp collisions at high transverse momenta p_T. A large part of the centrally produced $\bar{\Lambda}$'s at high p_T are found to originate from antistrange quark ($\bar{s}$) fragmentation. Therefore, the anti-Lambda polarization $P_{\bar{\Lambda}}$ is sensitive to the polarization of the antistrange sea in the polarized nucleon. Measurements of $P_{\bar{\Lambda}}$ in longitudinally polarized pp collisions can provide new insights in the spin-dependent quark distributions in particular $\Delta\bar{s}(x)$. In the transversely polarized case, similar studies can give some insights into the transversity distribution $\delta\bar{s}(x)$.

The studies can be extended to other (anti-)hyperons in a straightforward way. If high accuracy measurements can be carried out, this may provide a complementary path to flavor decomposition of the nucleon spin.

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