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Authors

Xu, Qing-hua
Liang, Zuo-tang
Sichtermann, Ernst

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

Qing-hua Xu[a,b], Zuo-tang Liang[a,b], and Ernst Sichtermann[b]

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

[b]*Nuclear Science Division, MS 70R0319,*

Lawrence Berkeley National Laboratory, Berkeley, CA 94720

Abstract

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 anti-strange sea of the nucleon. We make predictions using different parameterizations of the polarized quark distribution functions. The results show that the measurement of longitudinal anti-Lambda polarization can distinguish different parameterizations, and that similar measurements in the transversely polarized case can give some insights into the transversity distribution of the anti-strange 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, 3, 4, 5, 6, 7] and theoretically [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 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, it has been pointed out that 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, 22, 23, 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,

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

where η is the pseudo-rapidity of the $\bar{\Lambda}$, and $\Delta\sigma$ and σ are the polarized and unpolarized

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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,

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

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. 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 parameterizations 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 anti-hyperons $(\bar{H})$, $\Delta D_c^H(z)$ and $\Delta D_c^{\bar{H}}(z)$, have been made over the past decade [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. In particular, the polarized fragmentation functions have been calculated [8, 10, 14, 15, 16, 17, 18], for directly produced (anti-)hyperons that contain the fragmenting parton c using different models for the spin transfer factor $t_{H,c}^F$ $(t_{\bar{H},c}^F)$ 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 $\Delta D_c^H(z)$ 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

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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. Examples of this kind have been given in Ref.[17].

The production of high p_T Λ's in pp collisions is more involved than Σ^+ production. This is because their production 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 anti-quark 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 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 PYTHIA [31] in its default tune. Fig.1 shows the expected fractional contributions to $\bar{\Lambda}$ with $p_T \geq 8\text{GeV}$ as a function of the pseudo-rapidity η in pp collisions at $\sqrt{s} = 200\text{GeV}$. 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 $p_T \geq 8\text{GeV}$ 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 anti-strange sea polarization and that the size should be somewhat larger than that of the Λ.

Using the "standard" and the "valence" parameterizations for the polarized parton distributions in Ref. [32] and the parameterization for the unpolarized parton distributions in Ref. [33], we evaluated $P_{\bar{\Lambda}}$ as a function of η for $p_T \geq 8\text{GeV}$ using Eqs.(1-3). The results are presented in Fig.3. As in [10, 14, 15, 16, 17, 18], we used the SU(6) and DIS pictures for

the spin transfer factor $t_{\bar{H},c}^{F}$ from parton c to the hyperon $\bar{H}$ that contains the fragmenting c. The decay contributions from heavier anti-hyperons are taken into account in the same way as in [10, 14, 15, 16, 17, 18]. The second rank anti-hyperons and those from gluon fragmentation are taken as unpolarized. The different contributions to the $\bar{\Lambda}$ production are calculated using PYTHIA.

As expected, $|P_{\bar{\Lambda}}|$ 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 parameterizations of the polarized parton distributions is large. The latter difference originates predominantely from the differences in the parameterizations for $\Delta\bar{s}$ in the x region $0.05 < x < 0.25$ from which most $\bar{\Lambda}$'s with $p_T > 8\text{GeV/c}$ originate. 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 the calculations, we chose $p_T \geq 8\text{GeV}$ so that factorization theorem and pQCD calculations are expected to apply. We expect that the qualitative features of the results are similar at lower p_T. Given the size of the production cross section and the expected luminosities and polarizations, measurements at RHIC [34] should have a good chance to distinguish between the predictions based on different parameterizations of the polarized quark distributions. This provides a tool to study the polarization of the nucleon sea.

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

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

(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 anti-quarks. The partonic spin transfer factor for the elementary hard scattering process is replaced by $D_T^{a^{\uparrow}b \rightarrow c^{\uparrow}d}(y)$ for transverse polarization, which is also calculable from pQCD for the elementary hard scattering processes (see e.g. [35]).

As we have emphasized before, the results shown in Figs.1 and 2 are for unpolarized reactions. Just as in the longitudinally polarized case, the $\bar{\Lambda}$ polarization in the transversely polarized case is also dominated by the $\bar{s}$ fragmentation and spin contributions, and therefore

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$P_{\bar\Lambda,T}$ 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 $\delta q(x) = \Delta q(x)$. The results are given in Fig.4. The differences between the results in Fig.3 and 4 originate from the differences between $D^{\bar a b \to \bar c d}(y)$ 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 anti-strange quark ($\bar s$) fragmentation. Therefore, the anti-Lambda polarization $P_{\bar\Lambda}$ is sensitive to the polarization of the anti-strange sea in 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.

Acknowledgments

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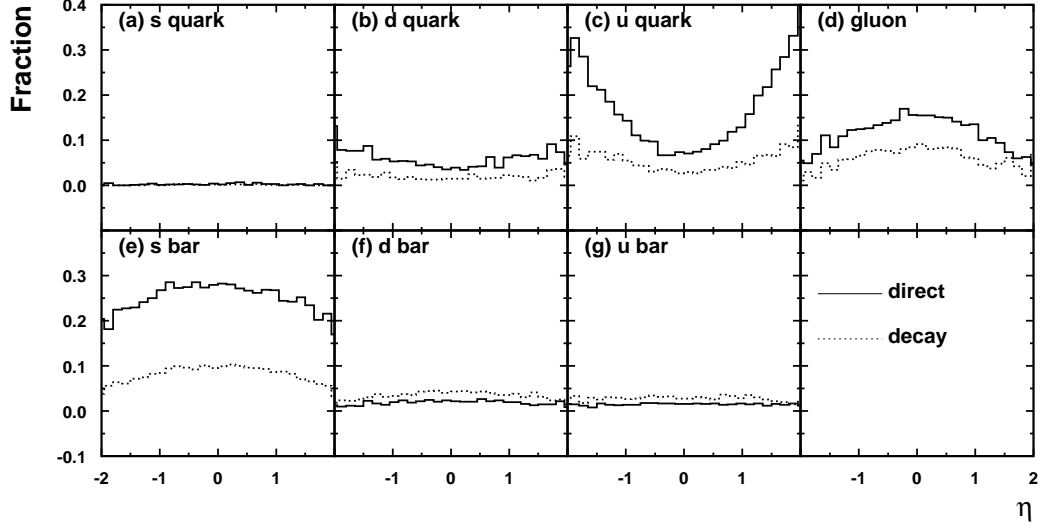
FIG. 1: Contributions to $\bar{\Lambda}$ production at $p_T \geq 8$ GeV/c in pp collisions at $\sqrt{s} = 200$ GeV. The solid and dashed lines are respectively the directly produced and decay contributions.
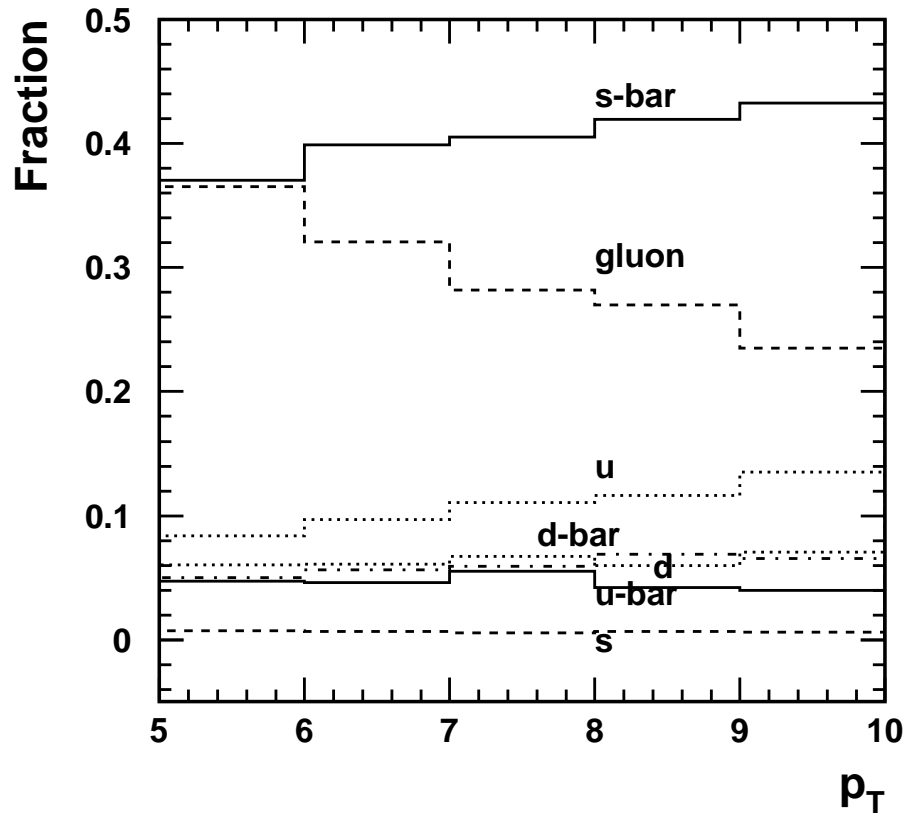
FIG. 2: Contributions to $\bar{\Lambda}$ production for $|\eta| < 1$ in pp collisions at $\sqrt{s} = 200$ GeV versus transverse momentum p_T.
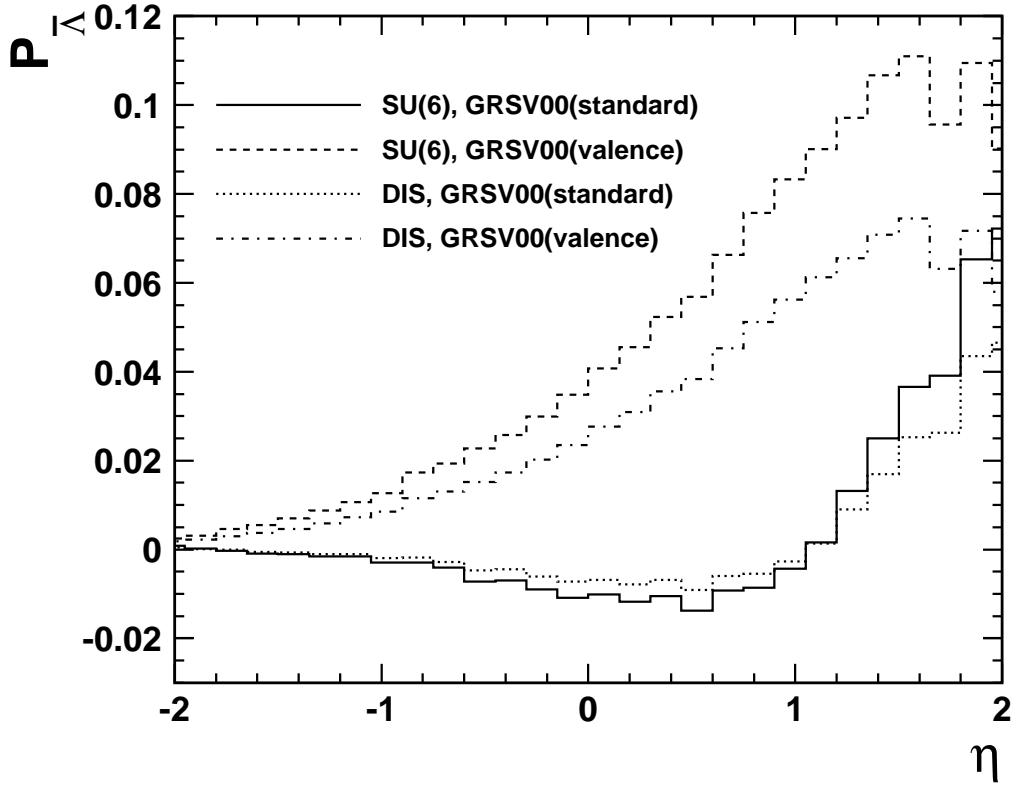
FIG. 3: Longitudinal $\bar{\Lambda}$ polarization for transverse momentum $p_T \geq 8$ GeV/c in pp collisions at $\sqrt{s} = 200$ with one longitudinally polarized beam versus pseudo-rapidity η of the $\bar{\Lambda}$. Positive η is taken along the polarized beam direction.
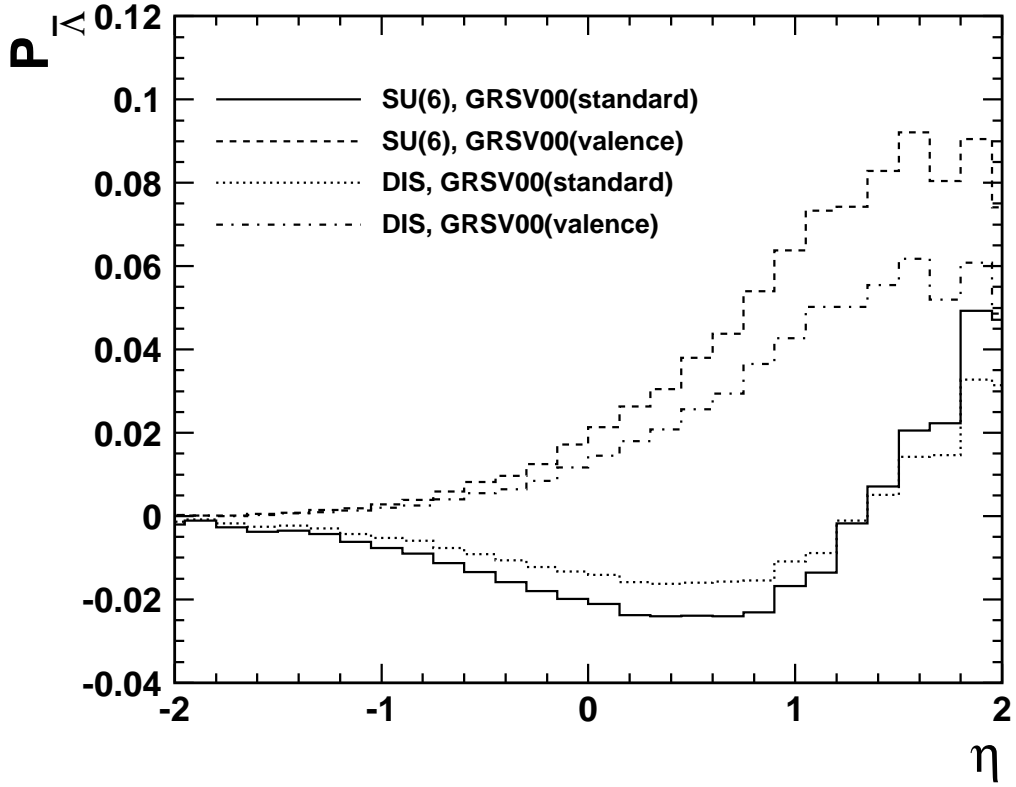
FIG. 4: Transverse $\bar{\Lambda}$ polarization for transverse momentum $p_T \geq 8$ GeV/c in pp collisions at $\sqrt{s} = 200$ with one transversely polarized beam versus pseudo-rapidity η of the $\bar{\Lambda}$. Positive η is taken along the polarized beam direction.