Longitudinal and transverse spin transfer to Λ and $\bar{\Lambda}$ hyperons in p+p collisions at STAR

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The longitudinal or transverse spin transfer to Lambda and anti-Lambda hyperons in polarized proton-proton collisions is expected to be sensitive to the helicity or transversity distributions of strange and anti-strange quarks of the proton, and to the corresponding polarized fragmentation function. We report the first measurement of the transverse spin transfer to Λ and $\bar{\Lambda}$ along the polarization direction of the fragmenting quark, D_{TT}, in transversely polarized proton-proton collisions at 200 GeV with the STAR experiment at RHIC. The data correspond to an integrated luminosity of 18 pb^{-1}, and cover a kinematic range of $|\eta|<$ 1.2 and transverse momentum p_T up to 8 GeV/c. We also report an improved measurement of the longitudinal spin transfer D_{LL} to Λ and $\bar{\Lambda}$ with p_T up to 6 GeV/c, using data with about twelve times larger figure-of-merit than the previously published STAR results. The prospects of hyperon polarization measurements in the forward pseudo-rapidity region (2.5<η<4) in p+p collision in the year of 2021 and beyond will also be discussed, which is based on the STAR forward detector upgrade plan including a forward tracking system and a forward calorimeter system.

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1. Introduction

The polarizations of Λ and $\bar{\Lambda}$ hyperons have been studied extensively in various aspects of spin effects in high energy reactions due to the self spin-analyzing parity violating decay. In particular, Λ polarization transferred from polarized lepton or hadron beams (usually referred to as spin "transfer") in different reactions provides a natural connection to polarized fragmentation functions and the polarized parton densities of the nucleon. A number of measurements have been made in polarized lepton-nucleon Deep Inelastic Scattering (DIS), and in polarized hadron-hadron collisions in the STAR experiment at RHIC. As the $s(\bar{s})$ quark plays a dominant role in $\Lambda(\bar{\Lambda})$ hyperon's spin content, the measurements of spin transfer to $\Lambda(\bar{\Lambda})$ hyperon provide a natural connection to the polarized parton distribution of (anti-)strange quarks in nucleon, which are not well constrained yet in experiment. In particular, the transverse spin transfer to Λ ($\bar{\Lambda}$) in hadron-hadron collisions provides a natural connection to transversity of (anti-)strange quarks through polarized fragmentation functions [1, 2, 3]. Similarly, the longitudinal spin transfer to Λ ($\bar{\Lambda}$) hyperons in hadron-hadron collisions provides sensitivity to the helicity distribution of (anti-)strange quarks [3, 4, 5, 6, 7, 8].

In this contribution, we report the first measurement of transverse spin transfer to Λ and $\bar{\Lambda}$ hyperons in transversely polarized proton-proton collisions at $\sqrt{s} = 200\,\text{GeV}$ with the STAR experiment at RHIC [9]. Then we report an improved STAR measurement of the longitudinal spin transfer D_{LL} to Λ and $\bar{\Lambda}$ hyperons in longitudinally polarized proton–proton collisions at $\sqrt{s} = 200\,\text{GeV}$ [10].

2. First measurement of transverse spin transfer to Λ and $\bar{\Lambda}$ hyperons at RHIC

The transverse spin transfer, D_{TT}, to the Λ in proton-proton collisions is defined as:

$$D_{\text{TT}} \equiv \frac{d\sigma^{(p^\uparrow p \to \Lambda^\uparrow X)} - d\sigma^{(p^\uparrow p \to \Lambda^\downarrow X)}}{d\sigma^{(p^\uparrow p \to \Lambda^\uparrow X)} + d\sigma^{(p^\uparrow p \to \Lambda^\downarrow X)}} = \frac{d\delta\sigma^\Lambda}{d\sigma^\Lambda}, \tag{2.1}$$

where $\uparrow(\downarrow)$ denotes the positive (negative) transverse polarization direction of the particles and $\delta\sigma^\Lambda$ is the transversely polarized cross section. Within the factorization framework, $\delta\sigma^\Lambda$ can be written as the convolution of parton transversity, polarized partonic cross section and the polarized fragmentation function [1].

The polarization of $\Lambda(\bar{\Lambda})$ hyperons, $P_{\Lambda(\bar{\Lambda})}$, can be measured from the angular distribution of the final state particles via their weak decay channel $\Lambda \to p\pi^-$ ($\bar{\Lambda} \to \bar{p}\pi^+$),

$$\frac{dN}{d\cos\theta^*} \propto A\left(1 + \alpha_{\Lambda(\bar{\Lambda})}P_{\Lambda(\bar{\Lambda})}\cos\theta^*\right), \tag{2.2}$$

where A is the detector acceptance varying with θ^* as well as other observables, $\alpha_{\Lambda(\bar{\Lambda})}$ is the weak decay parameter, and θ^* is the angle between the $\Lambda(\bar{\Lambda})$ polarization direction and the (anti-) proton momentum in the $\Lambda(\bar{\Lambda})$ rest frame. For the D_{TT} measurements, the transverse polarization direction of the outgoing fragmenting parton is used to obtain θ^*. Since there is a rotation along the normal direction of the scattering plane between the transverse polarization directions of incoming and outgoing quarks [11], the momentum direction of the outgoing parton is required and the reconstructed jet axis adjacent to the $\Lambda(\bar{\Lambda})$ is used as the substitute for the direction of the outgoing

fragmenting quark. Previously, only the spin transfer along the normal direction of the Λ production plane, D_{NN}, was measured with fixed target proton-proton collisions by the E704 Collaboration at Fermilab [12].

The data for the D_{TT} measurement here were collected at RHIC with the STAR experiment in the year 2012 with transversely polarized proton beams, which amount to an integrated luminosity of $18 \, \text{pb}^{-1}$. The average transverse polarizations for the two beams were 58 % and 64 %. The primary detector sub-system is the Time Projection Chamber (TPC) [13], which provides tracking for charged particles in the pseudo-rapidity range of $|\eta| < 1.3$ with full azimuthal coverage. The Barrel Electro-Magnetic Calorimeter (BEMC) [14] and Endcap Electro-Magnetic Calorimeter (EEMC) [15] were used in generating the pimary jet trigger information at STAR. The data sample here were recorded with Jet-Patch (JP) trigger conditions which required a transverse energy deposit in BEMC or EEMC patches (each covering $\Delta\eta \times \Delta\phi = 1 \times 1$) exceeding certain thresholds.

The Λ and Λ̄ candidates were reconstructed from their dominant weak decay channels, $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$, with a branching ratio of 63.9 % [16]. The selection procedure of Λ and Λ̄ candidates is based on the topology of the weak decay in a similar way as the previous longitudinal spin transfer measurement in Ref. [17]. In addition, reconstructed jets were employed to obtain the momentum direction of the fragmenting quark and thus the transverse polarization direction of hyperons for the D_{TT} measurement. Jets were reconstructed using the anti-k_T algorithm [18] and then the association between $\Lambda(\bar{\Lambda})$ candidates and the adjacent reconstructed jet was made by constraining the radius, $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.6$, between the $\Lambda(\bar{\Lambda})$ momentum direction and the jet axis in $\eta - \phi$ space. The bin counting method was used to obtain the raw yields of Λ and Λ̄ candidates. The signal mass windows were chosen to be about 3σ of the mass width. The residual background fractions r were estimated by the side-band method and found to be 7 % ~ 10 %. The background subtraction was done at the spin transfer level as $D_{TT} = (D_{TT}^{raw} - rD_{TT}^{bkg})/(1-r)$, with D_{TT}^{raw} and D_{TT}^{bkg} defined as the spin transfer for signal and side-band regions.

To minimize the systematics associated with acceptance and relative luminosity, D_{TT} for hyperon candidates has been extracted from the asymmetry in small $\cos\theta^*$ intervals using[9]:

$$D_{TT} = \frac{1}{\alpha P_{\text{beam}} \langle\cos\theta^*\rangle} \frac{\sqrt{N^\uparrow(\cos\theta^*)N^\downarrow(-\cos\theta^*)} - \sqrt{N^\downarrow(\cos\theta^*)N^\uparrow(-\cos\theta^*)}}{\sqrt{N^\uparrow(\cos\theta^*)N^\downarrow(-\cos\theta^*)} + \sqrt{N^\downarrow(\cos\theta^*)N^\uparrow(-\cos\theta^*)}}, \quad (2.3)$$

where $\alpha_\Lambda = 0.642 \pm 0.013$ [16], $\alpha_{\bar{\Lambda}} = -\alpha_\Lambda$, P_{beam} is the beam polarization and $\langle\cos\theta^*\rangle$ denotes the average value in the $\cos\theta^*$ interval. $N^{\uparrow(\downarrow)}$ is the Λ yield in the corresponding $\cos\theta^*$ bin when the proton beam is upward (downward) polarized. The relative luminosity between $N^\uparrow$ and $N^\downarrow$ is cancelled in this cross-ratio asymmetry. The acceptance is also cancelled as the acceptance in a small $\cos\theta^*$ interval is expected to remain the same when flipping the beam polarization [17].

The STAR results for D_{TT} versus hyperon p_T are shown in Fig. 1 for Λ and Λ̄ at both positive and negative η regions relative to the polarized beam in proton-proton collisions at $\sqrt{s} = 200 \, \text{GeV}$. These results provide the first measurements on transverse spin transfer of hyperons in proton-proton collisions at a high energy of $\sqrt{s} = 200$ GeV. The D_{TT} results for Λ and Λ̄ are consistent with zero within uncertainties. The data cover p_T up to $7 \, \text{GeV}/c$, where $D_{TT} = 0.031 \pm 0.033(\text{stat.}) \pm 0.008(\text{sys.})$ for Λ and $D_{TT} = -0.034 \pm 0.040(\text{stat.}) \pm 0.009(\text{sys.})$ for Λ̄ at $\langle\eta\rangle = 0.5$ and $\langle p_T \rangle = 6.7 \, \text{GeV}/c$. The data are comparable to a model estimation calculated at $\langle\eta\rangle = \pm 0.5$, which is available for RHIC energy, with simple assumptions of the transversity (using the DSSV08
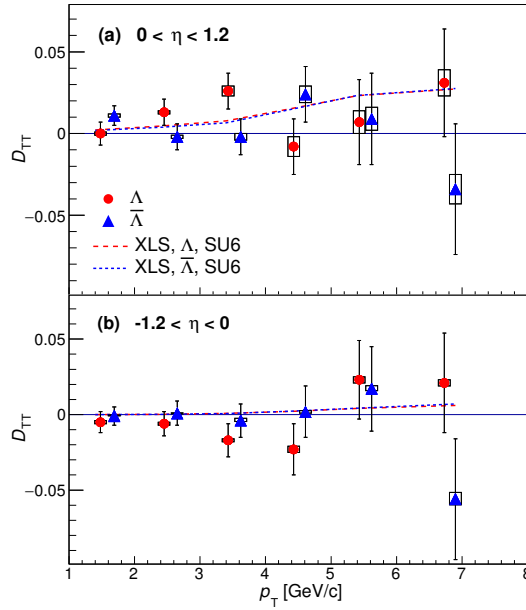
Figure 1: The spin transfer D_{TT} for Λ and $\bar{\Lambda}$ versus p_T in polarized proton-proton collisions at $\sqrt{s} = 200\,\text{GeV}$ at STAR [9], in comparison with model predictions [2, 3] for (a) positive η and (b) negative η. The vertical bars and hollow rectangles indicate the sizes of the statistical and systematic uncertainties, respectively. The $\bar{\Lambda}$ results have been offset to slightly larger p_T values for clarity.

helicity distribution as input) and the SU6 picture of fragmentation functions [2, 3]. Since strange and anti-strange quarks are expected to carry a significant part of the spins of Λ and $\bar{\Lambda}$, the measurements of transverse spin transfer to them can provide sensitivity to the transversity distribution of strange quarks. Knowledge on transversity of valence quarks has been learned mostly from DIS experiments, but the transversity distribution of (anti-)strange quarks is still poorly known in experiment [19, 20, 21].

3. Improved measurement of longitudinal spin transfer to Λ ($\bar{\Lambda}$) hyperons at STAR

The longitudinal spin transfer, D_{LL}, to Λ hyperon in polarized proton-proton collisions is defined as:

$$D_{LL} \equiv \frac{d\sigma_{p^+p \to \Lambda^+ X} - d\sigma_{p^+p \to \Lambda^- X}}{d\sigma_{p^+p \to \Lambda^+ X} + d\sigma_{p^+p \to \Lambda^- X}}, \tag{3.1}$$

where the superscripts $+$ or $-$ denote the helicity of the beam proton or the Λ hyperon.

The data sample for this analysis was recorded with the STAR experiment in 2009 and corresponds to an integrated luminosity of about $19\,\text{pb}^{-1}$ with an average longitudinal beam polarization, P_{beam}, of $57\,\% \pm 4.7\,\%$. The figure-of-merit of this data sample, $P_{\text{beam}}^2 \mathscr{L}$, is about twelve times higher than that of the previous STAR measurement of D_{LL} [17]. Similar to the 2012 data sample, the events here were recorded also with a jet-patch trigger condition in the BEMC or EEMC.

The reconstruction of $\Lambda(\bar{\Lambda})$ is similar to that done for the D_{TT} analysis. The detailed selection cuts were tuned in p_T intervals so as to keep as much signal as possible, while keeping the residual background at an acceptable level of about $10\,\%$. In addition, the Λ and $\bar{\Lambda}$ baryons were required to

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be associated with a reconstructed jet that satisfied the trigger conditions. Here, the jet sample was reconstructed using the mid-point cone algorithm, as in several previous STAR jet analyses [22, 23]. For this association, no significant difference is expected either for anti-kt or mid-point cone jet algorithm. The association required that the reconstructed Λ or Λ̄ candidate was within the jet cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.7$.

Following our previous D_{LL} measurement [17], the longitudinal spin transfer D_{LL} was extracted from the asymmetry:

$$D_{LL} = \frac{1}{\alpha_{\Lambda(\bar{\Lambda})}P_{\text{beam}}\langle\cos\theta^*\rangle}\frac{N^+ - RN^-}{N^+ + RN^-}, \tag{3.2}$$

where N^+ (N^-) is the number of Λ or Λ̄ candidates in the $\cos\theta^*$ interval when the beam is positively (negatively) polarized. $\langle\cos\theta^*\rangle$ is the average value of $\cos\theta^*$ in this interval, but different from the case for D_{TT}, here θ^* is defined as the angle between $\Lambda(\bar{\Lambda})$ momentum direction and the (anti-)proton momentum in the $\Lambda(\bar{\Lambda})$ rest frame. R denotes the relative luminosity ratio for these two beam polarization states and has been measured with Beam-Beam Counters [17].

Fig. 2 shows our new STAR results on the spin transfer D_{LL} to the Λ and to the Λ̄ as functions of p_T for positive η. The longitudinal spin transfer is found to be D_{LL} = -0.036 ± 0.048 (stat) ± 0.013 (sys) for Λ and D_{LL} = 0.032 ± 0.043 (stat) ± 0.013 (sys) for Λ̄ at $\langle\eta\rangle$ = 0.5 and $\langle p_T\rangle$ = 5.9 GeV/c. The data are compared with the theory expectations from Ref. [4], with D_{LL} for Λ and Λ̄ combined, and from Ref. [3], with D_{LL} separately for Λ and for Λ̄. The data are still consistent with zero within uncertainty, and also provide no evidence for a difference between Λ and Λ̄ D_{LL}. However, the data are below the DSV scenario 3 theory expectation assuming that the quark polarized fragmentation functions are flavor-independent [4].
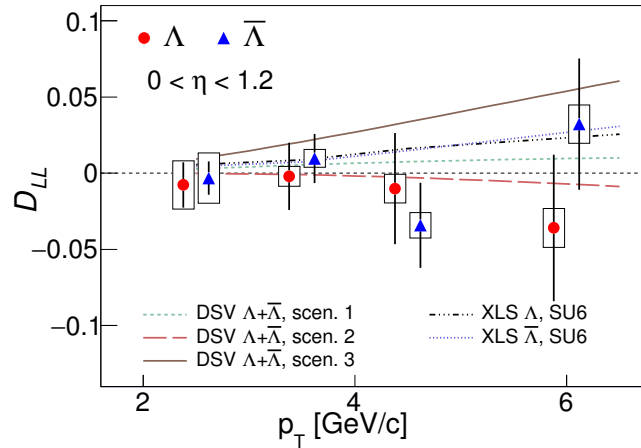

Figure 2: Comparison of the measured spin transfer D_{LL} from STAR 2009 data [10] with theory predictions for positive η versus hyperon p_T. The vertical bars and boxes indicate the sizes of the statistical and systematic uncertainties, respectively. The Λ̄ results have been offset to slightly larger p_T values for clarity.

4. Summary and Outlook

In summary, we report the first measurement of the transverse spin transfer, D_{TT}, to Λ and

$\bar{\Lambda}$ in transversely polarized proton-proton collisions at $\sqrt{s} = 200\,\text{GeV}$ at RHIC-STAR, and an improved measurement of the longitudinal spin transfer, D_{LL}, to Λ hyperons and $\bar{\Lambda}$ anti-hyperons in longitudinally polarized proton–proton collisions at $\sqrt{s} = 200\,\text{GeV}$ from STAR. The results for D_{TT} are found to be consistent with zero for Λ and $\bar{\Lambda}$ within uncertainties, and are also consistent with model predictions. The D_{LL} data do not provide evidence for a non-vanishing spin transfer within uncertainties, but tend to be below a model expectation based on the extreme assumption on polarized fragmentation functions.

STAR is expanding its acceptance by series of detector upgrades including inner sector upgrade of the Time Projection Chamber and the proposed forward detector upgrades [24], which would enable a number of interesting hyperon polarization measurements, including spin transfers D_{TT}, D_{LL} and other hyperon polarization measurements such as the induced transverse polarization in unpolarized proton-proton collisions, at very forward rapidities in proton-proton collisions.

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