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Measurement of Transverse Spin Transfer of Λ and $\bar{\Lambda}$ Hyperons in Polarized Proton+Proton Collisions at STAR

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The transverse spin transfer of Λ hyperons in proton+proton collisions can provide insights into the polarized fragmentation function and the transversity distribution of the nucleon. In this contribution we report the first measurement of the transverse spin transfer of Λ and $\bar{\Lambda}$ hyperons along the polarization direction of the fragmenting quark in transversely polarized proton+proton collisions at RHIC. The data were taken in 2012 with the STAR detector at $\sqrt{s} = 200\,\text{GeV}$ with an integrated luminosity of $18.4\,\text{pb}^{-1}$ and covered hyperon transverse momenta up to 8 GeV/c and η range of $-1.2 \sim 1.2$. The beam polarization was about 63% during our data taking period. The results of the transverse spin transfer, D_{TT}, are consistent with zero within uncertainties. The statistical uncertainty is ~ 0.04 at the highest p_{T} bin.

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1. Introduction

The spin structure of the proton remains a hot topic in QCD and the transverse spin structure is poorly known so far. The transverse spin transfer, $D_{\rm TT}$, can provide insights into the transversely polarized fragmentation function and the transversity distribution function. $\Lambda\,(\bar{\Lambda})$ (in the following denoted by Λ) hyperons have been widely used to study various aspects of spin effects in high-energy reactions for their self-analyzing parity violating decays [1]. $D_{\rm TT}$ of Λ is defined as the asymmetry of the cross sections of Λ with positive and negative polarizations when the incoming proton is polarized positively:

$$D_{\rm TT}^{\Lambda} = \frac{d\sigma^{(p^{\uparrow}p\to\Lambda^{\uparrow}X)} - d\sigma^{(p^{\uparrow}p\to\Lambda^{\downarrow}X)}}{d\sigma^{(p^{\uparrow}p\to\Lambda^{\uparrow}X)} + d\sigma^{(p^{\uparrow}p\to\Lambda^{\downarrow}X)}} = \frac{d\delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}, \tag{1.1}$$

where $\uparrow(\downarrow)$ denotes the positive (negative) polarization direction of the particles and $\delta\sigma^{\Lambda}$ is the transversely polarized cross section, which can be factorized into the convolution of the transversity distribution function, the transversely polarized partonic cross section and the transversely polarized fragmentation function [2]. The polarized partonic cross section is calculable using perturbative QCD.

We present the first measurement on transverse spin transfer along the fragmenting quark's polarization direction ($D_{\rm TT}$) to Λ in $p+p$ collisions at $\sqrt{s} = 200\,\text{GeV}$ taken in 2012 with the STAR detector in this contribution.

2. Analysis

The reconstruction of Λ hyperons was made through the weak decay channel with particle identification and topological selections applied. Jets were reconstructed and used as proxies of the fragmenting quarks in order to determine the transverse polarization direction of Λ. Then the correlation between Λ and jets was made. The "asymmetry method" was used in the extraction of $D_{\rm TT}$, which is similar as that used in the previous longitudinal spin transfer measurement [3] in the way that the asymmetry of cross sections with opposite beam polarization is applied to cancel the detector acceptance effect.

2.1 Λ Reconstruction and Jet Correlation

Λ and $\bar{\Lambda}$ candidates were identified from the topology of their dominant weak decay channels, $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$, respectively. Each of the two decay channels has a branching ratio of 63.9% [4].

The reconstructed event vertex was required to be along the beam axis and within 60 cm of the Time Projection Chamber (TPC) [5] center to ensure uniform tracking efficiency. A search was made in each event to find (anti-)proton and pion tracks of opposite curvature with an identification cut on track's dE/dx measured in the TPC. The tracks were paired to form Λ candidates and then topological selections were applied to further reduce the background. The topological selections included criteria for the distance of closest approach between the paired tracks, the distance between the point of closest approach and the beam collision vertex, and demanded that the momentum sum of the track pair pointed at the collision vertex. The values of the selection cuts were tuned in each

$p_{\rm T}$ bin to preserve signals while reducing the background fraction to 10% or less. The invariant mass distributions of the $p\pi^-$ and $\bar{p}\pi^+$ track pairs are shown in Fig. 1.

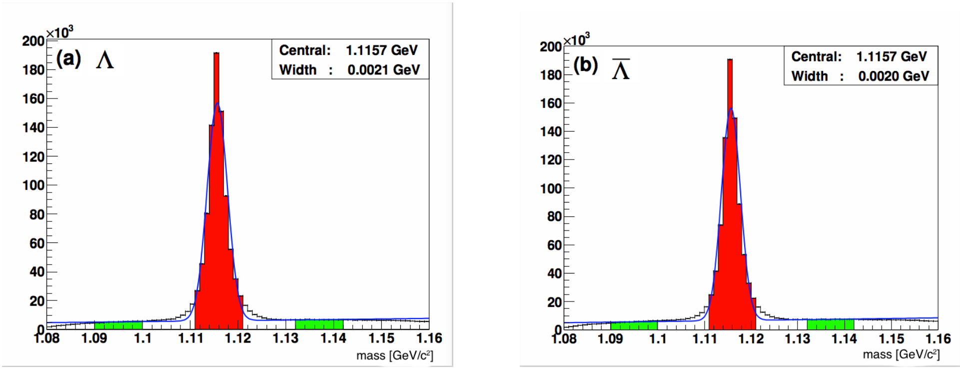

Figure 1: The invariant mass distributions of the paired (a) $p\pi^-$ and (b) $\bar{p}\pi^+$ after topological selections. The candidate events with $p_{\rm T}$ range of $2 \sim 3\,{\rm GeV/c}$ and η range of -1.2 $\sim$ 1.2 are shown in the plots for examples. The sideband events (green zone) were used to estimate the background fraction in the signal range (red zone) considering that the distribution of background is linear.

Jets were reconstructed using the anti-$k_{\rm T}$ algorithm [6] with a resolution parameter $R = 0.6$. Then a correlation between Λ candidates and the reconstructed jets was made by constraining the distance ($\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$) between Λ momentum direction and jet axis in $\eta - \phi$ space. An example of ΔR distribution is shown in Fig. 2. The Λ candidates in the jet near-side ($\Delta R < 0.6$) were used to measure $D_{\rm TT}$.

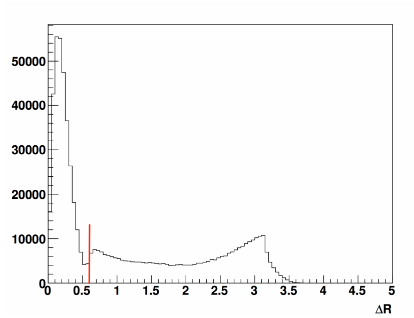

Figure 2: ΔR distribution of Λ candidates in the signal mass window of $1.111 \sim 1.121\,{\rm GeV/c^2}$ and $p_{\rm T}$ range of $2 \sim 3\,{\rm GeV/c}$.

2.2 Extraction of Transverse Spin Transfer

The polarization of Λ hyperons, P_Λ, can be measured via the weak decay channel $\Lambda \rightarrow p\pi^-$ ($\bar{\Lambda} \rightarrow \bar{p}\pi^+$) from the angular distribution of the final state in Λ's rest frame:

$$\frac{dN}{d\cos\theta^*} = \frac{N_{\rm tot}}{2} A(\cos\theta^*)(1 + \alpha_\Lambda P_\Lambda \cos\theta^*), \tag{2.1}$$

where $N_{\rm tot}$ is the total number of Λ produced in collisions, $\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013$ [4] is the decay parameter, θ^* is the angle between the proton momentum in the hyperon rest frame and the

Λ polarization direction and $A(\cos\theta^*)$ is the detector acceptance, which may depend on θ^* as well as other kinematic parameters (p_T).

The polarization direction of Λ needs to be determined in order to measure $D_{\rm TT}$. In this analysis, the transverse spin transfer along the fragmenting quark's polarization direction was measured, which means that the fragmenting quark's polarization direction was considered as the polarization direction of Λ. It is known that there is a rotation between the transverse polarization direction of incoming quark and that of the fragmenting quark around the normal of the scattering plane [7]. Therefore, the scattering angle is required and the jet momentum direction was used as the substitute of the momentum direction of fragmenting quark here.

To minimize the uncertainty associated with the detector acceptance effects, $D_{\rm TT}$ has been extracted through the asymmetry of Λ counts in small $\cos\theta^*$ intervals with opposite beam polarization:

$$D_{\rm TT} = \frac{1}{\alpha P_{\rm beam}\langle\cos\theta^*\rangle}\frac{N^{\uparrow}-RN^{\downarrow}}{N^{\uparrow}+RN^{\downarrow}}, \tag{2.2}$$

where α is the decay parameter [4], $P_{\rm beam}$ is the polarization of beam, $\langle\cos\theta^*\rangle$ is the average value in each small $\cos\theta^*$ bin, $N^{\uparrow}(N^{\downarrow})$ are the counts of hyperons in a small $\cos\theta^*$ interval when the beam is positively (negatively) polarized and R is the relative luminosity ratio for these two polarization states. The detector acceptance in this $\cos\theta^*$ interval is largely canceled because the acceptance in a small $\cos\theta^*$ interval is expected to be the same when flipping the beam spin which is essentially flipped every 100 to 200 ns.

$D_{\rm TT}$ were firstly obtained using Eq. 2.2 in each $\cos\theta^*$ bin, and then fitted with a constant in the $\cos\theta^*$ range of (-1,1), which is noted as $D_{\rm TT}^{\rm raw}$ since it was extracted from the raw counts including residual background in the signal mass window. An example of $D_{\rm TT}$ extraction versus $\cos\theta^*$ is shown in Fig. 3 (a) for Λ and Fig. 3(b) for $\bar{\Lambda}$ with $2 < p_{\rm T} < 3\,{\rm GeV/c}$ with the blue beam polarized. The spin asymmetry $\delta_{\rm TT}$ for K_S^0 was also extracted using the same procedure of D_{TT} (assuming $\alpha_{K_S^0}$=1), which is a null check (K_S^0 is spin zero), and the results shown in Fig. 3 (c) are consistent with zero as expected.

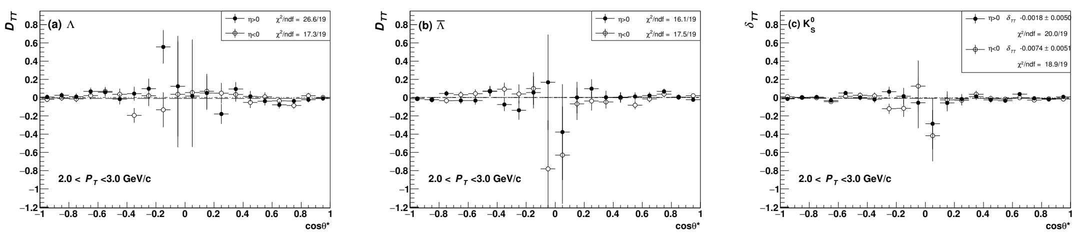

Figure 3: The transverse spin transfer $D_{\rm TT}$ versus $\cos\theta^*$ for (a) Λ and (b) $\bar{\Lambda}$ candidates, and (c) the spin asymmetry $\delta_{\rm TT}$ for the cross check sample of K_S^0 mesons versus $\cos\theta^*$. The filled circles show the results for positive η with respect to the polarized beam and the open circles show the results for negative η with the blue beam polarized. Only statistical uncertainties are shown here and the results were fitted with a constant.

Finally the physical $D_{\rm TT}^{\rm phy}$ ($D_{\rm TT}$ as follows) was obtained by correcting the average dilution factor from the residual background as Eq. 2.3.

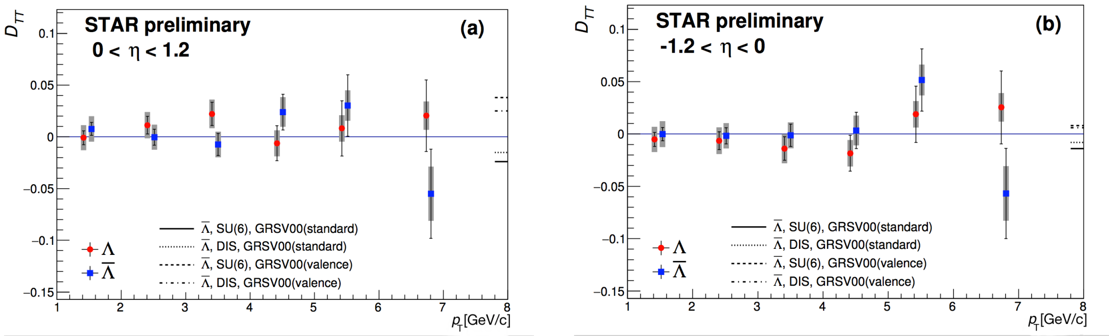

Figure 4: The transverse spin transfer D_{TT} versus p_{T} for Λ and $\bar{\Lambda}$ with (a) positive η with respect to the polarized beam and (b) with negative η with respect to the polarized beam. For clarity, the $\bar{\Lambda}$ data points have been shifted slightly in p_{T}. The horizontal lines show the model predictions for $\bar{\Lambda}$ with $p_{\mathrm{T}} > 8\,\mathrm{GeV/c}$ using different models [2]. The η of $\bar{\Lambda}$ in model calculations are (a) $\eta = +0.5$ and (b) $\eta = -0.5$.

$$D_{\mathrm{TT}} = \frac{D_{\mathrm{TT}}^{\mathrm{raw}} - rD_{\mathrm{TT}}^{\mathrm{bkg}}}{1-r}, \tag{2.3}$$

$$\delta D_{\mathrm{TT}} = \frac{\sqrt{(\delta D_{\mathrm{TT}}^{\mathrm{raw}})^2 + (r\delta D_{\mathrm{TT}}^{\mathrm{bkg}})^2}}{1-r}, \tag{2.4}$$

where $D_{\mathrm{TT}}^{\mathrm{bkg}}$ is calculated using the sideband events and r is the residual background fraction. The statistical uncertainty was estimated as Eq. 2.4.

2.3 Systematic Uncertainties

The systematic uncertainty for D_{TT} includes 2% [4] scale uncertainty from decay parameter measurement, 3.4% scale uncertainty beam polarization measurement, 0.012 from relative luminosity estimation, residual background fraction estimation, overlapping event (pile-up) effect and trigger bias. The first three entries were common to the results in all p_{T} bins and the rest are varying. These contributions were combined in quadrature to estimate the size of the total systematic uncertainties as they are considered to be independent.

The trigger conditions may introduce bias to D_{TT} measurement. The effects were studied with Monte Carlo simulation events that were generated using the Perugia 2012 tune [8] in PYTHIA 6.428 [9] and passed through the STAR detector response package based on GEANT 3 [10]. This part includes the bias of the fractional momentum, relative fraction of subprocess & fragmenting parton flavor and the relative fraction of feed-down. The systematic uncertainty from trigger bias varies from 0.002 to 0.023 with increase of hyperon p_{T}.

3. Results

The results of D_{TT} as a function of p_{T} are shown in Fig. 4 for Λ and $\bar{\Lambda}$ at both positive and negative η regions in $p+p$ collisions at $\sqrt{s} = 200\,\mathrm{GeV}$ at STAR. The statistical and systematic uncertainties are shown with vertical bar and grey band. The results for Λ and $\bar{\Lambda}$ are consistent with each other and both consistent with zero within uncertainties. There is no strong dependence on p_{T} in current results.

Fig.4 also shows the comparison between measurement results and model calculations. The horizontal lines show the calculations for $\bar{\Lambda}$ with $p_{\mathrm{T}} > 8\,\mathrm{GeV/c}$ using different models from [2], which calculated D_{TT} for $\bar{\Lambda}$ versus η in $p+p$ collisions at RHIC energy based on simple assumptions of the transversity and the fragmentation function. The model calculations are made at $\eta = \pm 0.5$, whereas the data covers the range $0 < |\eta| < 1.2$. The comparison shows model calculations are consistent with the measured D_{TT} results at the highest p_T bin within uncertainty.

4. Summary

The first measurement on transverse spin transfer of Λ and $\bar{\Lambda}$ in $p+p$ collisions at $\sqrt{s} = 200\,\mathrm{GeV}$ with the STAR detector at RHIC was reported and covers Λ and $\bar{\Lambda}$ hyperons' p_{T} range of $1 \sim 8\,\mathrm{GeV/c}$ and η range of $-1.2 \sim 1.2$. The results of D_{TT} are consistent with zero within uncertainties. The precision of D_{TT} is ~ 0.04 at $\langle p_{\mathrm{T}} \rangle = 6.7\,\mathrm{GeV/c}$.

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