Measurement of Transverse Spin Transfer of $\Lambda$ and $\bar{\Lambda}$ in Transversely Polarized Proton+Proton Collisions at RHIC-STAR

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Outline

- Motivation
- Experiment Setup
- $\Lambda(\bar{\Lambda})$ Reconstruction
- Measurement Method
- $D_{TT}$ Measurement Results
- Summary
**Motivation**

- Transversely polarized cross section of hyperons could be parameterized into three parts:

\[ d\Delta_T\sigma^{(p\perp p\rightarrow H\perp X)} \propto \sum_{abcd} \int dx_a \, dx_b \, dz \, \delta f_a(x_a) f_b(x_b) d\Delta_T\sigma^{(a \perp b \rightarrow c \perp d)} \Delta_T D_c^H(z) \]


Crucial elements for the study of nucleon spin structure:
- transversity distribution
- pQCD calculation
- transversely polarized fragmentation function

- The transverse spin transfer is defined as:

\[ D^H = P^H = \frac{d\sigma^{(p\perp p\rightarrow H\perp X)} - d\sigma^{(p\perp p\rightarrow H\parallel X)}}{d\sigma^{(p\perp p\rightarrow H\perp X)} + d\sigma^{(p\perp p\rightarrow H\parallel X)}} = \frac{d\Delta_T\sigma}{d\sigma} \]

- The transverse spin transfer provides insights into transversely polarized fragmentation function and transversity distribution function.
Frames and Azimuthal Distributions

- $\Lambda (\bar{\Lambda})$ polarization can be extracted from the angular distribution of its decay product in its rest frame.

$$\frac{d\sigma}{d\cos\theta^*} \propto (1 + \alpha_{\Lambda(\bar{\Lambda})} P_{\Lambda(\bar{\Lambda})}\cos\theta^*)$$

$\alpha$: decay parameter
- 0.642 for $\Lambda$ and -0.642 for $\bar{\Lambda}$
- $P_{\Lambda}$: polarization of $\Lambda (\bar{\Lambda})$

$\theta^*$: the angle between decay particle (proton) momentum in $\Lambda$'s rest frame and the direction of $\Lambda$ polarization

In transverse case, azimuthal angle of polarization needs to be determined which is not needed in longitudinal case.

- $D_{TT}$: the spin transfer along the polarization of outgoing quark considering the rotation in scattering plane.

In this analysis, reconstructed jet axis is used as substitute of the outgoing quark momentum direction.

J.Collins et al, NPB420 (1994)565
The Relativistic Heavy Ion Collider (RHIC) is the first and only polarized proton collider in the world.


RHIC Beam polarization: blue beam: 64%, yellow beam: 58%.
Sub detectors involved in this analysis:

- **TPC**: Time Projection Chamber $\eta \sim (-1.2, 1.2)$
  Track reconstruction of charged particles and charged particle identification.

- **BEMC**: Barrel Electromagnetic Calorimeter $\eta \sim (-1.0, 1.0)$
  For triggering.
**Λ and \( \bar{\Lambda} \) Reconstruction**

- Applied topological cuts to reconstruct \( \Lambda \) and \( \bar{\Lambda} \) via their decay channels: \( \Lambda \rightarrow p\pi^- \) and \( \bar{\Lambda} \rightarrow \bar{p}\pi^+ \)

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**Central :** 1.1157 GeV  
**Width :** 0.0021 GeV  
**Bkg Frac. :** 0.0716

**Central :** 1.1160 GeV  
**Width :** 0.0034 GeV  
**Bkg Frac. :** 0.0660

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**Central :** 1.1157 GeV  
**Width :** 0.0020 GeV  
**Bkg Frac. :** 0.0812

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**Central :** 1.1163 GeV  
**Width :** 0.0021 GeV  
**Bkg Frac. :** 0.0751

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**Central :** 1.1158 GeV  
**Width :** 0.0025 GeV  
**Bkg Frac. :** 0.0683

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**Central :** 1.1158 GeV  
**Width :** 0.0042 GeV  
**Bkg Frac. :** 0.0731

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**Central :** 1.1168 GeV  
**Width :** 0.0034 GeV  
**Bkg Frac. :** 0.0683
**Λ and ¯Λ Reconstruction**

- Applied topological cuts to reconstruct Λ and ¯Λ via their decay channels: $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$

### Raw yields of Λ and ¯Λ after selection

<table>
<thead>
<tr>
<th>$p_T$ [GeV/c]</th>
<th>Λ</th>
<th>¯Λ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1~2</td>
<td>490 k</td>
<td>544 k</td>
</tr>
<tr>
<td>2~3</td>
<td>323 k</td>
<td>382 k</td>
</tr>
<tr>
<td>3~4</td>
<td>183 k</td>
<td>201 k</td>
</tr>
<tr>
<td>4~5</td>
<td>78 k</td>
<td>74 k</td>
</tr>
<tr>
<td>5~6</td>
<td>32 k</td>
<td>26 k</td>
</tr>
<tr>
<td>6~8</td>
<td>20 k</td>
<td>14 k</td>
</tr>
<tr>
<td>Total</td>
<td>1126 k</td>
<td>1242 k</td>
</tr>
</tbody>
</table>

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**DIS17, Jincheng Mei**
Δ and ¯Δ Reconstruction

• Applied topological cuts to reconstruct Δ and ¯Δ via their decay channels: \(Δ \rightarrow pπ^-\) and \(\bar{Δ} \rightarrow \bar{p}π^+\)

<table>
<thead>
<tr>
<th>P_T [GeV/c]</th>
<th>Δ</th>
<th>Δ̄</th>
</tr>
</thead>
<tbody>
<tr>
<td>1~2</td>
<td>490 k</td>
<td>544 k</td>
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</tr>
</tbody>
</table>

Background fraction is estimated by side bands.

The obtained \(D_{raw}\) and their statistical uncertainties were corrected for the residual background:

\[
D_{TT} = \frac{D_{raw}^{TT} - rD_{TT}^{bkg}}{1 - r}
\]

\[
\delta D_{TT} = \sqrt{(\delta D_{TT}^{raw})^2 + (r\delta D_{TT}^{bkg})^2}
\]

\(r\) : residual background fraction
Jet Correlation

- Use anti-Kt algorithm to reconstruct jet then make correlation to a $\Lambda$ ($\bar{\Lambda}$) by calculating $\Delta R$.
- Request $\eta_{jet} \sim (-0.7, 0.9)$, $P_T > 5.0$ GeV/c, neutral fraction of Jet < 0.95.
  If $\Delta R < 0.6$ (near side), we use the jet momentum direction as outgoing quark direction to obtain quark’s polarization direction.

$$\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$$

$$\Delta \phi = \phi_\Lambda - \phi_{jet}$$

$$\Delta \eta = \eta_\Lambda - \eta_{jet}$$
Measurement Method

- Based on the relationship between polarization of $\Lambda (\bar{\Lambda})$ and the angular distribution of its decay product in its rest frame.

$$\frac{d\sigma}{d\cos\theta^*} \propto (1 + \alpha_{\Lambda (\bar{\Lambda})} P_{\Lambda (\bar{\Lambda})} \cos\theta^*)$$

- In this analysis, $D_{TT}$ is extracted from the asymmetry of $\Lambda$ counts with opposite beam polarization in a small $\cos\theta^*$ bin:

$$D_{TT} = \frac{\frac{1}{\alpha P_{\text{beam}} \langle \cos \theta^* \rangle} \left( N^\uparrow - R N^\downarrow \right)}{N^\uparrow + R N^\downarrow}$$

$P_{\text{beam}}$: polarization of beam
$\langle \cos \theta^* \rangle$: mean in each $\cos\theta^*$ bin
$N^\uparrow$: $\Lambda (\bar{\Lambda})$ counts with positive beam polarization
$N^\downarrow$: $\Lambda (\bar{\Lambda})$ counts with negative beam polarization
$R$: relative luminosity

- Acceptance of reverse beam polarization is expected to be the same in each $\cos\theta^*$ bin, and thus cancelled.
Extraction of Spin Transfer $D_{TT}$

$\Lambda$ counts versus $\cos\theta^*$ with opposite beam polarization. Separate the whole range of $\cos\theta^*$ into 20 bins.

$D_{TT}$ extraction in each $\cos\theta^*$

$$D_{TT} = \frac{1}{\alpha P_{\text{beam}} < \cos\theta^* >} \frac{N^\uparrow - RN^\downarrow}{N^\uparrow + RN^\downarrow}$$

Fit the 20 $D_{TT}$ with a constant.
Fitted result as the $D_{TT}$ in the $p_T$ bin.

The method passed the null check with $K_S^0$
Systematic Uncertainty

- 3.4% scale uncertainty from RHIC beam polarization measurement.
  —obtained from the polarimetry group of RHIC

- 2% from decay parameter (0.642 ± 0.013).
  —PDG

- 0.012 from relative luminosity measurement.

- Residual background fraction estimation.
  —Compare two methods of residual background fraction (fit and side-band)

- Trigger bias estimated from MC simulation.

- Pileup effect.

- The sum of systematic uncertainty is range of 0.012 ~ 0.026
Results of $D_{TT}$

- Results of transverse spin transfer $D_{TT}$ of $\Lambda$ and $\bar{\Lambda}$ in p+p collision at 200 GeV.

- Most precise measurement on $\Lambda(\bar{\Lambda})$ polarization in p+p collision at RHIC, which reach $p_T \sim 8$ GeV/c with statistical uncertainty of 0.04.

- The dominant source of systematic uncertainty is from relative luminosity in low $p_T$.

- $D_{TT}$ of $\Lambda$ and $\bar{\Lambda}$ are consistent with each other and consistent with zero at the current precision.
Summary

- First measurement on transverse spin transfer of $\Lambda(\bar{\Lambda})$ in p+p collisions, which can provide insights into transversely polarized fragmentation function and nucleon transversity distribution.

- The $\Lambda(\bar{\Lambda})$ sample is the largest so far in p+p collision at RHIC and the precision of $D_{TT}$ is $\sim0.04$ at $p_T \sim8$ GeV/c for $\Lambda(\bar{\Lambda})$.

- $D_{TT}$ of $\Lambda$ and $\bar{\Lambda}$ are consistent with each other and consistent with zero at the presently available precision.
Thanks for Your Attention!
Backup
Previous Results

- Previous measurement of transverse spin transfer.
  - Only $D_{NN}$ spin transfer w.r.t. production plane (Fermilab E704 Collaboration, 1997).

$D_{NN}$: spin transfer along normal direction of $\Lambda$ production plane.

Significant spin transfer was found at large $x_F$.
Comparison for different substitutes of outgoing quark momentum direction:
1. jet direction
2. hyperon direction
Theory Prediction

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

The spin asymmetry for $K_S^0$ was also extracted, which is used as a null check ($K_S^0$ is spin zero), and the results are consistent with zero as expected. It is also a good check for acceptance assumption.
Pileup Effect Estimation

Plot of Lambda yield vs. collision rate.

Four beam polarization sets in RHIC p+p collision: ++, +- , -+, --.

The factor \( u \) for each set is the difference between linear fit and constant fit at collision rate = 20kHz.

The uncertainty of \( D_{TT} \) from pileup effect is estimated by:

\[
(\delta D_{TT}^{\text{sys.pileup}})^2 = \sum_{k=++,-+,--,+-,--} \left[ D_{TT}(n^k) - D_{TT}((1-u^k)n^k) \right]^2
\]