Azimuthal Transverse Single-Spin Asymmetries of Inclusive Jets and Identified Hadrons Within Jets in Polarized pp Collisions at $\sqrt{s} = 200$ GeV

Ting Lin (林挺), for the STAR Collaboration
Shandong University (山东大学)
Challenges in Transverse Single-Spin Asymmetry

- Large transverse single-spin asymmetry ($A_N$) at forward rapidities has been observed in transversely polarized proton-proton collisions;
- pQCD predicts very small asymmetries in the hard scattering process;
- Twist-3 and transverse momentum dependent (TMD) frameworks are developed to describe this transverse spin effect.

$$A_N = \frac{N_L - N_R}{N_L + N_R}$$
Collins Effect

- Correlation between the polarization of a scattered quark and the momentum of a hadron fragment transverse to the scattered quark direction;
- Collins effect combines the quark transversity in the proton with the spin-dependent Collins fragmentation function;
- \[ D_{h/q,S_q}(z,j_T) = D_{h/q}(z,j_T) + \frac{1}{z M_h} H_1^{1q}(z,j_T) \vec{S}_q \cdot (\hat{p}_q \times \vec{j}_T). \]
Transverse Single-Spin Asymmetry

- For pions within jets, the spin dependent cross section is:

\[
d\sigma^\uparrow(\phi_S, \phi_H) - d\sigma^\downarrow(\phi_S, \phi_H)
\]

\[
\sim d\Delta\sigma_0 \sin(\phi_S) + d\Delta\sigma_1^- \sin(\phi_S - \phi_H) + d\Delta\sigma_1^+ \sin(\phi_S + \phi_H) + d\Delta\sigma_2^- \sin(\phi_S - 2\phi_H) + d\Delta\sigma_2^+ \sin(\phi_S + 2\phi_H)
\]

\[
A^{\sin(\phi)}_{UT} = \frac{\sigma^\uparrow(\phi) - \sigma^\downarrow(\phi)}{\sigma^\uparrow(\phi) + \sigma^\downarrow(\phi)} \frac{\sum_{a,b,c} h_1^a(x_1, \mu) f_b(x_2, \mu) \sigma^\text{Collins}_{ab \rightarrow c} H_{1,h/c}^{++}(z_h, j_T; Q)}{\sum_{a,b,c} f_a(x_1, \mu) f_b(x_2, \mu) \sigma_{ab \rightarrow c}^{\text{unpol}} D_{h/c}(z_h, j_T; Q)}
\]

- Collins effect in pp involves a mixture of collinear and TMD factorization:
  - Initial hard scattering involves the collinear transversity \( h_1^a \);
  - Polarized quark then fragments according to the TMD Collins fragmentation function \( H_{1,h/c}^{++} \);

- Cleaner kinematic separation of transversity and TMD physics than previous SIDIS measurements;

- At EIC, full jet reconstruction will enable similar kinematic separation.

Zhong-Bo Kang et al., JHEP 11, 068 (2017) and PLB 774, 635 (2017)

May, 2022

Ting Lin - DIS 2022

Umberto D'Alesio et al. PRD 83, 034021 (2011)
Relativistic Heavy Ion Collider (RHIC)

- World’s first and only polarized proton+proton collider;
  - Provide polarized proton+proton collisions up to 510 GeV;
- Spin pattern changes from fill to fill with little depolarization;
  - Siberian snakes preserve the polarization;
  - Spin rotators select spin orientation;
  - proton-Carbon (pC) polarimeters and hydrogen gas jet (H-Jet) measure the polarization.
Solenoidal Tracker At RHIC (STAR)

- TOF: $|\eta| < 1$
- BEMC: $|\eta| < 1$
- TPC: $|\eta| < 1$
- EEMC: $1 < \eta < 2$

Magnet

May, 2022
Ting Lin - DIS 2022
STAR Data and Kinematic Coverage

- STAR covers a similar range in momentum fraction to that of SIDIS experiments but at much higher $Q^2$;
- 200 GeV results provide better statistical precision at larger momentum fraction regions while 500 GeV results probe lower values.
- These two different energies provide experimental constraints on evolution effects and insights into the magnitude and nature of TMD observables that will be measured at EIC.

<table>
<thead>
<tr>
<th>Year</th>
<th>2011</th>
<th>2012</th>
<th>2015</th>
<th>2017</th>
<th>2022</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ (GeV)</td>
<td>500</td>
<td>200</td>
<td>200</td>
<td>510</td>
<td>510</td>
</tr>
<tr>
<td>$L_{\text{int}}$ (pb$^{-1}$)</td>
<td>25</td>
<td>22</td>
<td>52</td>
<td>350</td>
<td>$\sim$400</td>
</tr>
<tr>
<td>Polarization</td>
<td>53%</td>
<td>57%</td>
<td>57%</td>
<td>58%</td>
<td>$\sim$52%</td>
</tr>
</tbody>
</table>

May, 2022

Ting Lin - DIS 2022
Jet Reconstruction

Anti-$k_t$ Algorithm:
• Radius = 0.6;
• Less sensitive to underlying event and pile-up effects;
• Used in both data and simulation;

Simulation: PYTHIA 6.4 Perugia 2012 with additional tuning to STAR data;

Three Simulation Levels:
• Parton – hard scattered partons involved in 2->2 hard scatterings from PYTHIA;
• Particle – partons propagate and hadronize into stable and color-neutral particles;
• Detector – detector response to the stable particles.

May, 2022

Ting Lin - DIS 2022
Data and simulation are in agreement;

The measured jet kinematics are corrected back to particle level in the final results.
Underlying Event and Particle Identification

- Particle jet $p_T$ values are corrected for underlying event activity measured using the off-axis cone method;
- Spin asymmetries are corrected for the dilution from the underlying event contribution;
- Good particle identification from TPC and TOF.
π± Azimuthal Distribution in Jets

• Theoretical expectations are based on the DMP+2013 model (Umberto D’Alesio et.al., PLB 773, 300 (2017)) that combines quark transversity from SIDIS with the Collins FF from $e^+e^-$ collisions.
\[ \pi^\pm \] Azimuthal Distribution in Jets

- DMP+2013 model from Umberto D’Alesio et al., PLB 773, 300 (2017);
- KPRY model from Zhong-Bo Kang et al., PLB 774, 635 (2017);
- Both assume universality and factorization.
π± Azimuthal Distribution in Jets

- Collins TMD FF is sensitive to the \((j_T, z)\) dependence;
- Our results slightly favor the KPRY model than DMP+2013;
- Sizable differences between data and both theoretical calculations.

May, 2022

Ting Lin - DIS 2022
Comparison with 500 GeV Results

• The asymmetries agree at $0.06 < x_T < 0.2$, $Q^2$ differ by a factor of 6;

• Collins asymmetry has a weak energy dependence in hadronic collisions;

• $z$ and $j_T$ dependences of the Collins FF are closely related.

$K^\pm$ and Proton Azimuthal Distribution in Jets

- $K^+$, with contribution from favored fragmentation of $u$ quarks, has similar magnitude of asymmetries to $\pi^+$;
- $K^-$, which is produced by unfavored fragmentation, has asymmetries that are consistent with zero;
- Proton and anti-proton’s asymmetries are all consistent with zero at one sigma level.

May, 2022

Ting Lin - DIS 2022
Summary

• The most precise measurements to date of the TSSA for charged hadrons inside jets in hadronic interactions are presented;

• The asymmetries agree with previous measurement at $\sqrt{s} = 500$ GeV, indicating a weak energy dependence of Collins effect in hadronic collisions;

• The asymmetries for charged pions are larger than the theoretical calculations which may indicate larger quark transversity;

• The Collins asymmetries for charged kaons and protons are statistically limited, need further measurements to confirm the difference due to fragmentation.