Single Spin asymmetries in Longitudinally Polarized SIDIS

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1 Introduction — experimental observables

2 Twist-3 TMD distributions in spectator diquark model

3 Longitudinally polarized beam and target SSAs
   • Beam spin asymmetry
   • Longitudinal target spin asymmetry
Longitudinally polarized beam SSA

- Longitudinally polarized lepton beam off unpolarized nucleon target:
  \[ e \rightarrow (l) + N(P) \rightarrow e(l') + h(P_h) + X \]

- Beam single spin asymmetry (SSA) of pion in SIDIS:
  \[ A(\phi)_{LU} = \frac{1}{P} \frac{N_{\rightarrow} - N_{\leftarrow}}{N_{\rightarrow} + N_{\leftarrow}}, \quad A_{LU}^{\sin \phi} = \frac{2}{PN} \sum_{i=1}^{N} \sin \phi_i \]

  Measured by CLAS (04’, 14’) and HERMES (06’) for neutral and charged pions.
  Preliminary data for kaon and proton from HERMES.
Beam SSAs of $\pi^\pm$, $\pi^0$ measured by HERMES, PLB648,164(2007).

$A_{LU}^{\sin\phi}$ and $\tilde{A}_{LU}^{\sin\phi}$: VM contribution included and subtracted:

$E_{beam} = 27.6$ GeV
Experimental measurements of beam SSA

- Beam SSA of $\pi^0$ ($E_{beam} = 5.776$ GeV) measured by CLAS, PLB704,397(2011):

- Beam SSA of charged and neutral pions at 5.5 GeV (CLAS Collaboration, 2014)
Longitudinally polarized target SSA

- Unpolarized lepton beam off longitudinally polarized nucleon target:
  \[ e(l) + N \rightarrow (P) \rightarrow e(l') + h(P_h) + X \]

- Longitudinal target SSA:
  \[ A(\phi)_{UL} = \frac{1}{N \rightarrow -N \leftarrow} P \frac{N \rightarrow +N \leftarrow}{N}, \quad A_{UL}^{\sin \phi} = \frac{2}{PN} \sum_{i=1}^{N} \sin \phi_i \]
Longitudinally polarized target SSA

- CLAS preliminary results (QCD-N’12)

\[ A_{UL} \sin \phi \]

\[ P_T \text{ (GeV)} \]

\[ x \]
**Mechanism for $A_{LU}^{\sin \phi}$ and $A_{UL}^{\sin \phi}$**

- Longitudinal spin-dependent structure functions:

$$
\frac{d\sigma}{dx \, dy \, d\psi \, dz \, d\phi_h \, dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ \lambda e \, \sqrt{2\varepsilon (1-\varepsilon)} \, \sin \phi_h \, F_{LU}^{\sin \phi_h} \\
+ S_{||} \, \sqrt{2\varepsilon (1+\varepsilon)} \, \sin \phi_h \, F_{UL}^{\sin \phi_h} + \cdots \right\}
$$

- Most of data are in the region $P_T < 1$ GeV, where TMD formalism is a natural choice.

- TMD framework at leading-twist can not account those SSAs $A_{LU}^{\sin \phi}$ and $A_{UL}^{\sin \phi}$ may be interpreted by the TMD twist-3 distribution functions or TMD fragmentation functions.

- Although TMD factorization at subleading-twist has not been established, here we assume the tree-level TMD factorization at twist-3 is valid.
Mechanism for $A_{LU}^{\sin \phi}$ and $A_{UL}^{\sin \phi}$

- Beam spin asymmetry:

$$F_{LU}^{\sin \phi} = \frac{2M}{Q} \mathcal{C} \left[ \frac{\hat{P}_T \cdot p_T}{zM_h} \left( \frac{M_h}{M} f_1 \frac{\tilde{G}_1}{z} + x eH_1 \right) + \frac{\hat{P}_T \cdot k_T}{M} \left( \frac{M_h}{M} h_1 \frac{\tilde{E}}{z} + x g_1 D_1 \right) \right]$$

- Longitudinal target spin asymmetry

$$F_{UL}^{\sin \phi} = \frac{2M}{Q} \mathcal{C} \left[ \frac{\hat{P}_T \cdot p_T}{zM_h} \left( x h_L H_1 + \frac{M_h}{M} g_1L \frac{\tilde{G}_1}{z} \right) + \frac{\hat{P}_T \cdot k_T}{M} \left( x f_L D_1 - \frac{M_h}{M} h_{1L} \frac{\tilde{H}}{z} \right) \right]$$

- Involving twist-3 TMD distribution functions and fragmentation functions
quark-quark correlator at twist-3 (Bacchetta et al., 06):

\[
\Phi(x, k_T) = \ldots + \frac{M}{2P^+} \left\{ e - i e_s \gamma_5 - e^T \frac{e_{T}^{\rho \sigma} k_{T \rho} S_{T \sigma}}{M} \right.
\]

\[
+ f^\perp \frac{\not{\phi} T}{M} - f'^{\perp} \epsilon_T^{\rho \sigma} \gamma_\rho S_{T \sigma} - f_s^{\perp} \frac{\epsilon_T^{\rho \sigma} \gamma_\rho k_{T \sigma}}{M}
\]

\[
+ g'_T \gamma_5 S_T + g_s^{\perp} \gamma_5 \frac{\not{\phi} T}{M} - g^{\perp} \gamma_5 \frac{\epsilon_T^{\rho \sigma} \gamma_\rho k_{T \sigma}}{M}
\]

\[
+ h_s \left[ \frac{\eta^+, \eta^-}{2} \right] + h_T^{\perp} \left[ \frac{S_T, \not{\phi} T}{2M} \right] + i h \left[ \frac{\eta^+, \eta^-}{2} \right] \}
\]

### T-even

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### T-odd

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Status on model calculation of twist-3 TMDs

- So far no available fitting for twist-3 TMDs
- Model calculations provide primary information of twist-3 TMDs
- Commonly used models:
  - bag model
  - chiral soliton model
  - spectator diquark model
  - light-cone constituent quark model
Introduction — experimental observables
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spectator diquark model

\[ \Phi \sim \sum_X \int d^3 P_X <PS|\bar{\psi}(0)X > <X|\psi(0)|PS > \]

- Correlator can be calculated by inserting a complete set of final states

- In spectator diquark model, the unobserved (spectator) final states \(|X>\) are truncated and are approximated by the diquark states \(|qq>\), which have certain quantum numbers (scalar or vector particle)

- The nucleon-quark-diquark effective vertex

\[ <X|\psi(0)|PS > \approx \begin{cases} \frac{i}{k-m} \Gamma_s(k^2)U(P, S), & \text{scalar diquark;} \\ \frac{i}{k-m} \Gamma^\mu_v(k^2)U(P, S), & \text{axial-vector diquark.} \end{cases} \]
spectator diquark model

Diagram to calculate $\Phi(x, k_T)$ in DIS

- **T-even TMDs**
  \[
  \frac{M}{P^+} e(x, k_{T}^2) = \frac{1}{2} \text{Tr}[\Phi]
  \]
  \[
  S_L \frac{M}{P^+} h_L(x, k_{T}^2) = \frac{1}{2} \text{Tr}[\Phi \sigma^{+-} \gamma_5]
  \]

- **T-odd TMDs**
  \[
  \frac{\epsilon_T^{\alpha \rho} k_T^{\rho}}{P^+} g^\perp(x, k_{T}^2) = -\frac{1}{2} \text{Tr}[\Phi \gamma^\alpha \gamma_5]
  \]
  \[
  S_L \frac{\epsilon_T^{\alpha \rho} k_T^{\rho}}{P^+} f_L^\perp(x, k_{T}^2) = -\frac{1}{2} \text{Tr}[\Phi \gamma^\alpha].
  \]
Two sets of TMDs are calculated, by choosing different polarization sum of the vector diquark, as well as different relation between quark flavors and diquark types.

Results of $xg^\perp(x, k_T^2)$ in set 1

results of $xg^\perp(x, k_T^2)$ in set 2
Selected results of T-odd TMDs — $f_{L}^{\perp}(x, k_{T}^{2})$

- results of $f_{L}^{\perp}(x, k_{T}^{2})$ in two different sets
Selected results of T-even TMDs — $h_L$

- Results of $h_L(x, k_T^2)$ in two different sets

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**Zhun Lu**

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Beam SSA of $\pi^0$

$$F_{LU}^\sin \phi \approx \frac{2M}{Q} C \left[ \frac{\hat{P}_T \cdot k_T}{M} \left( x g^\perp D_1 \right) - \frac{\hat{P}_T \cdot p_T}{M_h} \left( x e H_1^\perp \right) \right]$$

- Isospin symmetry $\Rightarrow$ in $\pi^0$ production, $e H_1^\perp$ term is negligible:

$$H_1^\perp \pi^0/q = \left( H_1^\perp f^\text{av} + H_1^\perp \text{unf} \right)/2 \approx 0$$

- Recent extraction of Collins function (Anselmino et al., arXiv:1303.3822):
Beam SSA of $\pi^0$ vs $x$ at CLAS (5.776 GeV) in set 1

- T-odd distribution $g_{T}^{\perp}$ is crucial for beam SSA of neutral pion
Beam SSA of charged and neutral pion production at CLAS in set 2

- Data from CLAS Collaboration (2014)
- T-even distribution contributes significantly to beam SSA of positive pion
Longitudinal target spin asymmetry at HERMES (27.6 GeV)

- $\sin \phi_h$ asymmetry (target is longitudinally polarized):

$$A_{UL}^{\sin \phi_h} = \frac{F_{UL}^{\sin \phi_h}}{F_{UU}}$$

- In Wandura-Wilzcek approximation:

$$F_{UL}^{\sin \phi} \approx \frac{2M}{Q} C \left[ \frac{\hat{P}_T \cdot p_T}{z M_h} x h_L H_1^1 + \frac{\hat{P}_T \cdot k_T}{M} x f_L^1 D_1 \right]$$

- Longitudinal target spin asymmetry at HERMES (27.6 GeV):

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$A_{UL}$ for $\pi^0$ at CLAS

- $A_{UL}$ for $\pi^0$ at CLAS

Kinematics at CLAS:

$$E_e = 5.5\ \text{GeV}, \ 0.1 < x < 0.6, \ 0.4 < z < 0.7,$$

$$Q^2 > 1\ \text{GeV}^2, \ P_T > 0.05\ \text{GeV}, \ W^2 > 4\ \text{GeV}^2.$$
$A_{UL}$ for charged pion at CLAS

\begin{itemize}
  \item $A_{UL}$ for charged pion at CLAS
\end{itemize}
$A_{UL}$ for $\pi^0$ at COMPASS

$A_{UL}$ for $\pi^0$ at COMPASS

![Graph showing $A_{UL}$ for $\pi^0$ at COMPASS]

Kinematics at COMPASS:

$0.004 < x < 0.7$, $y > 0.1$, $0.2 < z < 0.9$,

$x_F > 0$, $Q^2 > 1\text{ GeV}^2$, $0.1\text{GeV} < P_T < 1\text{ GeV}$,

$5\text{GeV} < W < 18\text{GeV}$.
\( A_{UL} \) for charged pion at COMPASS
**Summary & Conclusion**

- Twist-3 TMDs distributions of $u$ and $d$ valence quarks are calculated in the spectator diquark model.
- Twist-3 TMDs play important roles in longitudinal beam and target SSAs.
- T-odd twist-3 distributions are essential for the SSA of $\pi^0$ production.
Summary & Conclusion

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Thank you for your attention