Some recent developments in single transverse-spin asymmetry

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Nuclear Theory Seminar
Jefferson Lab, Newport News, VA, Mar 09, 2009

based on work with J. -W. Qiu, Sterman, Vogelsang, and Yuan
Outline

- Introduction

- Collinear factorization approach:
  - Basic formalism (LO)
  - Evolution of twist-3 correlations (beyond LO)
  - Physical meaning of twist-3 correlations

- Phenomenology for future experimental measurements:
  - open charm
  - pT dependence
  - test of universality of Sivers function: W program

- Summary
Single transverse-spin asymmetry: definition

Consider scattering of a transversely-polarized spin-1/2 hadron ($\vec{s}_p$, $p$) with another hadron (or photon), observing a particle of momentum $\ell$

\[ p^\uparrow p \rightarrow \pi X \]

Spin-avg cross section:
\[ \sigma(\ell) = \frac{1}{2} [\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})] \]

Spin-dep cross section:
\[ \Delta \sigma(\ell, \vec{s}) = \frac{1}{2} [\sigma(\ell, \vec{s}) - \sigma(\ell, -\vec{s})] \]

Single transverse-spin asymmetry (SSA):
\[ A_N \equiv \frac{\Delta \sigma(\ell, \vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell, \vec{s}) - \sigma(\ell, -\vec{s})}{\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})} \]
Experimental status of Single Spin Asymmetry (SSA)

- Fermilab E704, STAR, PHENIX, BRAHMS, COMPASS, HERMES, JLab

\[ p^\uparrow p \rightarrow \pi X \]

SSA:

\[ A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \]

SSAs are observed in various experiments at different \( \sqrt{s} \).
SSA corresponds to a T-odd triplet product

- SSA measures the correlation between the hadron spin and the production plane, which corresponds to $\vec{s}_p \cdot (\vec{p} \times \vec{\ell})$

$$p^\uparrow p \rightarrow \pi(\ell) X$$

- Such a product is odd (naive) under time reversal (T-odd), and thus they can arise in a time-reversal invariant theory (e.g., QCD) only when there is a phase between different spin amplitudes.

$$A_N \propto i\vec{s}_p \cdot (\vec{p} \times \vec{\ell})$$

- The phase "i" is required by time-reversal invariance

- Covariant form: $A_N \propto i\varepsilon^{\mu\nu\alpha\beta} p_\mu s_\nu \ell_\alpha p'_\beta$

Nonvanishing $A_N$ requires a phase, a helicity flip, and enough vectors to fix a scattering plane
Non-vanishing SSA due to transverse motion

- If partons are purely collinear:
  
  \[ \sigma(s_T) \sim \text{generate phase from loop diagrams, proportional to } \alpha_s \]
  
  \[ \text{helicity is conserved for massless partons, helicity-flip is proportional to current quark mass } m_q \]

  Therefore we have
  
  \[ A_N \sim \alpha_s \frac{m_q}{\sqrt{s}} \rightarrow 0 \]

- \[ A_N \neq 0: \text{ result of parton’s transverse motion or correlations!} \]
Two mechanisms to generate SSA in QCD

- **TMD approach**: Transverse Momentum Dependent distributions probe parton’s intrinsic transverse momentum
  - Sivers function: in Parton Distribution Function (PDF)
  - Collins function: in Fragmentation Function (FF)

- **Collinear factorization approach**: Efremov-Teryaev 82, 84, Qiu-Sterman 91, 98
  - twist-3 multiparton correlation functions

- They apply in different kinematic domain:
  - TMD approach: need TMD factorization
    - Physical processes with two observed scales: $Q$ and $q$ ($Q \gg q$) with the large $Q$ to ensure a hard collision, while the $q \sim k_T$ probes parton’s transverse momentum
  - Collinear factorization approach: more relevant for single scale hard process

- They generate same results in the region when they both apply
  - Ji, Qiu, Vogelsang, Yuan, 2006
  - see also, A. Bacchetta, et.al., 2008
SSA in collinear factorization approach

- When all observed scales $>> \Lambda_{\text{QCD}}$, collinear factorization should work:

$$\sigma(s_T) \sim \sigma^{(a)} + \sigma^{(c)} + \ldots \Rightarrow \Delta \sigma(s_T) \sim \text{Re}[\sigma^{(a)}] \cdot \text{Im}[\sigma^{(c)}]$$

- How it works:

  1. Phase: from hard scattering amplitudes (unpinched pole)
  2. Spin flip: from interference between a quark state and a quark-gluon composite state

- Twist-3 quark-gluon correlation function $T_{q,F}(x,x)$:

$$T_{q,F}(x,x) = \int \frac{dy^-_1 dy^-_2}{4\pi} e^{ixP^+y_1^-} \langle P, s_T | \bar{\psi}_q(0) \gamma^+ \left[ \epsilon^{s_T\sigma n\bar{n}} F^+_\sigma(y_2^-) \right] \psi_q(y^-_1) | P, s_T \rangle$$
**Twist-3 approach: initial success (I)**

- Describe E704 data well with one parameter $\lambda_F$ (valence quark approx.)

Model:

\[
T_{u,F}(x,x) = \lambda_F \phi_u(x) \\
T_{d,F}(x,x) = -\lambda_F \phi_d(x)
\]

$\lambda_F = 0.07$ GeV  

Qiu, Sterman 1999
There are more than just the quark-gluon correlation. What about the others?

\[ T_{q,F}(x, x) = N_q x^{\alpha_q} (1 - x)^{\beta_q} \phi_q(x) \]
Twist-3 trigluon correlation functions

- Diagonal tri-gluon correlations:
  \[ T_G(x, x) = \int \frac{dy_1^- dy_2^-}{2\pi} e^{ixP^+ y_1^-} \times \frac{1}{xP^+} \langle P, s_T | F^+_{\alpha}(0) \left[ \epsilon^{\sigma T \sigma \tilde{n}} F_{\sigma}^{+(y_2^-)} \right] F^{\alpha+}(y_1^-) | P, s_T \rangle \]

- Two tri-gluon correlation functions - different color factors
  \[ T_G^{(f)}(x, x) \propto if^{abc} F^a F^c F^b = F^a F^c [T^c]^{ab} F^b \]
  \[ T_G^{(d)}(x, x) \propto d^{abc} F^a F^c F^b = F^a F^c [D^c]^{ab} F^b \]
  Fermionic correlation: \[ T_F(x, x) \propto \bar{\psi}_i F^c [T^c]_{ij} \psi_j \]

- D-meson production in Semi Inclusive Deep Inelastic Scattering (SIDIS):
  - Clean probe for twist-3 tri-gluon correlation functions

Ji, 1992; Kang, Qiu, 2008
Kang, Qiu, Vogelsang, Yuan, 2008
**D-meson production in SIDIS:  \( ep^\uparrow \rightarrow e + D + X \)**

- **Frame for SIDIS:**
  \[
  e(k) + p^\uparrow(P) \rightarrow e(k') + D(P_h) + X
  \]
  \[
  q = k - k' \quad z_h = \frac{P \cdot P_h}{P \cdot q} = \frac{E_h}{\nu}
  \]

- **Dominated by the contribution from trigluon correlations**

- **Single transverse-spin asymmetry:**
  \[
  A_N = \frac{\sigma(s_\perp) - \sigma(-s_\perp)}{\sigma(s_\perp) + \sigma(-s_\perp)} = \frac{d\Delta\sigma(s_\perp)}{dx_BdydzhdP_{h\perp}^2d\phi} / \frac{d\sigma}{dx_BdydzhdP_{h\perp}^2d\phi}
  \]
Production rate of D-meson in SIDIS

- Production rate (spin averaged):

\[
\frac{d\sigma}{dx_B dy dz_h dP_{h\perp}^2 d\phi} = \sigma_U^0 + \sigma_U^1 \cos \phi + \sigma_U^2 \cos 2\phi
\]

- \[z_h = \frac{P \cdot P_h}{P \cdot q} = \frac{E_h}{\nu}\]

- \(z_h\): Energy fraction of photon carried by D-meson

COMPASS

- Reasonable production rate, small \(\phi\) dependence

EIC

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Features of the SSA in SIDIS

- Dependence of tri-gluon correlation functions:

  \[ D - \text{meson} \propto T_G^{(f)} + T_G^{(d)} \]
  \[ \bar{D} - \text{meson} \propto T_G^{(f)} - T_G^{(d)} \]

  Separate \( T_G^{(f)} \) and \( T_G^{(d)} \) by the difference between \( D \) and \( \bar{D} \).

- \( A_N \) depends on \( T_G(x,x) \) and its derivative:

  \[ A_N \propto \epsilon \frac{1}{t} \frac{-x}{G(x)} \left( \frac{d}{dx} T_G(x,x) \right) \rightarrow 1/(1-x) \]

  Since \( x \) has a minimum at \( z_h \sim 0.5 \) (from kinematics constrain), SSA should have a minimum if the derivative term dominates.

- Model for tri-gluon correlation functions:

  \[ T_G^{(f,d)}(x,x) = \lambda_{f,d} G(x) \]
  \[ \lambda_{f,d} = \pm \lambda_F = \pm 0.07 \text{ GeV} \]
Estimation of SSA in D-meson production in SIDIS

- SSA for D⁰ production ($T_G^{(f)}$ only)

- Derivative term dominates, and small $\phi$ dependence
- Asymmetry is twice if $T_G^{(d)} = +T_G^{(f)}$, or zero if $T_G^{(d)} = -T_G^{(f)}$
- Opposite for the $\bar{D}$ meson
- Asymmetry has a minimum ~ $z_h$ ~ 0.5

Measure the SSAs ⇒ extract tri-gluon correlations

Test QCD: universality of tri-gluon correlations?
D-meson production in hadronic collisions: \( p^\uparrow p \rightarrow D + X \)

- Two partonic subprocesses:

  \[ p^\uparrow p \rightarrow D + X \]

  (a)

  (b)

- Quark-antiquark annihilation:

  (a)

  (b)

  (c)

  (d)

- Gluon-gluon fusion:

  (a)

  (b)

  (c)

  (d)
Spin-dependent cross section for D-meson production

- SSA from both quark-gluon correlation $T_{q,F}(x,x)$ and tri-gluon correlation $T_G(x,x)$

\[
E_{P_h} \frac{d^3 \Delta \sigma}{d^3 P_h} \bigg|_{gg \to c\bar{c}} = \frac{\alpha_s^2}{S} \sum_{i=f,d} \int \frac{dz}{z^2} D_{c\to h}(z) \int \frac{dx'}{x'} \phi_g/B(x') \int \frac{dx}{x} \sqrt{\frac{4\pi\alpha_s}{z\tilde{u}}} \left( \epsilon P_{sTn\bar{n}} \right) \delta \left( \tilde{s} + \tilde{t} + \tilde{u} \right) \times \left[ \left( T_G^{(i)}(x,x) - x \frac{d}{dx} T_G^{(i)}(x,x) \right) H_{gg\to c}(\tilde{s},\tilde{t},\tilde{u}) + T_G^{(i)}(x,x) \mathcal{H}_{gg\to c}(\tilde{s},\tilde{t},\tilde{u}) \right]
\]

- depends on correlation and its derivative
- same factorized form for qq subprocess

- Features of SSA:

When $c \to \bar{c}$
- hard parts do NOT change sign for $T_{q,F}$ and $T_G^{(f)}$
- hard parts change sign for $T_G^{(d)}$

\[
\Rightarrow \text{SSA will be very different for D and } \bar{D} \text{ if } T_G^{(d)} \neq 0
\]
\[
\Rightarrow \text{SSA will be very similar for D and } \bar{D} \text{ if } T_G^{(d)} = 0
\]
Rapidity dependence of D-meson production

**SSA at RHIC:**
\[ \sqrt{s} = 200 \text{ GeV} \quad \mu = \sqrt{m_c^2 + P_{h\perp}^2} \quad m_c = 1.3 \text{ GeV} \]

Solid: \( (1) \lambda_f = \lambda_d = 0.07 \text{ GeV} \quad T_G^{(d)} = T_G^{(f)} \)
Dotted: \( (2) \lambda_f = -\lambda_d = 0.07 \text{ GeV} \quad T_G^{(d)} = -T_G^{(f)} \)
Dashed: \( (3) \lambda_f = \lambda_d = 0 \quad T_G^{(d)} = T_G^{(f)} = 0 \)

D meson: Largest \( A_N \) happens when \( T_G^{(d)} = +T_G^{(f)} \)
\( \bar{D} \) meson: Largest \( A_N \) happens when \( T_G^{(d)} = -T_G^{(f)} \)
Without tri-gluon correlation, SSA is too small to be observed.

As a twist-3 effect, the SSAs fall off as $1/P_T$ when $P_T >> m_c$.
Recent progress on tri-gluon correlation

- Tri-gluon correlation contribution to the following processes have been studied
  - Drell-Yan: \( p^\uparrow p \rightarrow [\gamma^* \rightarrow \ell \bar{\ell}] + X \)
  - Single inclusive hadron: \( p^\uparrow p \rightarrow \pi + X \)
  - Direct photon: \( p^\uparrow p \rightarrow \gamma + X \)

- A new global fitting with both \( T_{q,F}(x,x) \) and \( T_G(x,x) \) is on the way

Comparing with SSA for single inclusive pion data from:
- E704
- STAR
- PHENIX
Strong scale dependence of SSA

- So far, all the calculations for SSA are at leading order (LO)
  \[ \Delta \sigma(Q, s_T) = \frac{1}{Q} H_1(Q/\mu_F, \alpha_s) \otimes f_2(\mu_F) \otimes f_3(\mu_F) + \mathcal{O}\left(\frac{1}{Q^2}\right) \]

- LO result has a strong scale dependence
  - Evolution of correlation function (long-distance distributions)
  - NLO correction (short-distance contribution beyond LO)

- Question: what are the complete set of correlation functions?

Recall: Leading twist (DGLAP evolution equation)
- unpolarized PDFs: \( q(x), G(x) \)
- helicity distributions: \( \Delta q(x), \Delta G(x) \)

Twist-3 spin dependent correlations:
- two sets of correlation functions
Evolution distinguishes QCD from parton model

- Parton model: Bjorken scaling (point particles)
  \[ F_2(x) = \sum_q e_q^2 x \phi_q(x) \]
  confirmed in the 1970s at SLAC

- QCD is much richer:
  \[ Q_0^2 < Q^2 \]

- DGLAP evolution equation:
  \[
  \frac{\partial}{\partial \ln \mu^2} \begin{pmatrix}
  q(x, \mu^2) \\
  g(x, \mu^2)
  \end{pmatrix}
  = \frac{\alpha_s(\mu^2)}{2\pi} \int_x^1 \frac{dy}{y} \begin{pmatrix}
  P_{qq} & P_{qg} & P_{gg}
  \end{pmatrix}
  \begin{pmatrix}
  q \\
  g
  \end{pmatrix}
  \begin{pmatrix}
  x \\
  \mu^2
  \end{pmatrix}
  \]

Friedman, Kendall, 1972

\[ x=0.25 \]
Scaling violation and evolution has been confirmed

- NLO DGLAP (scale dependence) for both PDF and Helicity Distribution Function (HDF) describes data very well

unpolarized structure function $F_2$

polarized structure function $g_1$
Twist-3 three-parton correlations

Set I: spin-averaged twist-2 PDFs + an operator insertion

\[ \tilde{T}_{q,F} = \int \frac{d y_1^- d y_2^-}{(2\pi)^2} e^{i x^+ P^+ y_1^-} e^{i x^+ P^+ y_2^-} \langle P, s_T | \bar{\psi}_q(0) \frac{\gamma^+}{2} \left[ e^{s T \bar{s} n n \sigma n n} F_\sigma^+(y_2^-) \right] \psi_q(y_1^-) | P, s_T \rangle \]

\[ \tilde{T}_{f,d}^{\Delta q,F} = \int \frac{d y_1^- d y_2^-}{(2\pi)^2} e^{i x^+ P^+ y_1^-} e^{i x^+ P^+ y_2^-} \frac{1}{P^+} \langle P, s_T | F^{++}(0) \left[ e^{s T \sigma n n \sigma n n} F_\sigma^+(y_2^-) \right] F^{++\lambda}(y_1^-) | P, s_T \rangle (-g_\rho \lambda) \]

Set II: spin-dependent twist-2 HDFs + an operator insertion

\[ \tilde{T}_{\Delta q,F} = \int \frac{d y_1^- d y_2^-}{(2\pi)^2} e^{i x^+ P^+ y_1^-} e^{i x^+ P^+ y_2^-} \langle P, s_T | \bar{\psi}_q(0) \frac{\gamma^+ \gamma^5}{2} \left[ i s_T \sigma F_\sigma^+(y_2^-) \right] \psi_q(y_1^-) | P, s_T \rangle \]

\[ \tilde{T}_{\Delta G,F}^{(f,d)} = \int \frac{d y_1^- d y_2^-}{(2\pi)^2} e^{i x^+ P^+ y_1^-} e^{i x^+ P^+ y_2^-} \frac{1}{P^+} \langle P, s_T | F^{++}(0) \left[ i s_T \sigma F_\sigma^+(y_2^-) \right] F^{++\lambda}(y_1^-) | P, s_T \rangle (i \epsilon_{\perp} \rho \lambda) \]

Two possible color contractions: if \( f_{abc}, d_{abc} \)

⇒ Two tri-gluon correlation functions

- \( T^{(f)} \) connects to gluon Sivers function
- \( T^{(d)} \) has no connections to TMD distribution
Feynman diagram representation

Diagrams:

Lagrangian → Feynman rules
Cross section → Feynman diagrams

Operator definition → Cut vertices
Perturbative change ← Feynman diagrams

Same diagram can represent different correlation functions depending on cut vertices

Cut vertices in the light-cone gauge:

\[
\mathcal{V}_{q,F}^{LC} = \frac{\gamma^+}{2P^+} \delta \left( x - \frac{k^+}{P^+} \right) x_2 \delta \left( x_2 - \frac{k_2^+}{P^+} \right) \left( i \epsilon^{sT\sigma n\bar{n}} \right) \left[ -g_{\sigma\mu} \right] C_q ,
\]

\[
\mathcal{V}_{G,F}^{LC} = x(x + x_2) (-g_{\alpha\beta}) \delta \left( x - \frac{k^+}{P^+} \right) x_2 \delta \left( x_2 - \frac{k_2^+}{P^+} \right) \left( i \epsilon^{sT\sigma n\bar{n}} \right) \left[ -g_{\sigma\mu} \right] C_{g}^{(f,d)} ,
\]

likewise for: \( \mathcal{V}_{\Delta q,F}^{LC}, \mathcal{V}_{\Delta G,F}^{LC} \)
Evolution kernels

- Feynman diagrams:

- Leading order for flavor non-singlet channel:
1. All kernels are infrared safe
2. Diagonal term is the same as DGLAP
3. Singlet terms are different for quark and anti-quark
   ⇒ they evolve differently (from tri-gluon correlations)
Diagonal contribution - Gluons:

\[
\frac{\partial T^{(d)}_{G,F}(x, x, \mu_F)}{\partial \ln \mu_F^2} = \frac{\alpha_s}{2\pi} \int_x^1 \frac{d\xi}{\xi} \left\{ P_{gg}(z) T^{(d)}_{G,F}(\xi, \xi, \mu_F) \right. \\
+ \frac{C_A}{2} \left[ 2 \left( \frac{z}{1-z} + \frac{1-z}{z} + z(1-z) \right) \left[ T^{(d)}_{G,F}(\xi, x, \mu_F) - T^{(d)}_{G,F}(\xi, \xi, \mu_F) \right] \\
+ 2 \left( 1 - \frac{1-z}{2z} - z(1-z) \right) T^{(d)}_{G,F}(\xi, x, \mu_F) + (1+z) T^{(d)}_{\Delta G,F}(x, \xi, \mu_F) \right. \\
\left. + P_{gg}(z) \left( \frac{N_c^2 - 4}{N_c^2 - 1} \right) \sum_q \left[ T_{q,F}(\xi, \xi, \mu_F) + T_{\bar{q},F}(\xi, \xi, \mu_F) \right] \right\}
\]

likewise for \( T^{(f)}_{G,F}(x, x, \mu_F) \)

1. Similar features as in quark case:
   - IR safe, diagonal term same as DGLAP
2. \( T^{(d)}_G \) has no connection to TMD distribution. One may argue that \( T^{(d)}_G = 0 \), however,
   Evolution can generate \( T^{(d)}_G \) as long as \( \sum_q \left[ T_{q,F} + T_{\bar{q},F} \right] \neq 0 \)
**Q^2 - Dependence of correlation functions**

- u-quark-gluon
- Tri-gluon

- Follow DGLAP for large $x$
- Large deviation in small $x$ region (large coherence)

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What can we learn from twist-3 correlation functions?

Set I: \[ \int dy^- \epsilon^{s_T \sigma n \bar{n}} F^+_\sigma(y^-) \]

Set II: \[ \int dy^2_- e^{ix_2 P^+ y^2_-} [i s^\sigma_T F^+_\sigma(y^2_-)] \]

Consider a classical (Abelian) situation:

- change of transverse momentum
  \[ \frac{d}{dt} p'_2 = e(\vec{v}' \times \vec{B})_2 = -ev_3 B_1 = ev_3 F_{23} \]

- in the c.m. frame
  \[ (m, \vec{0}) \rightarrow \bar{n} = (1, 0, 0_T), \quad (1, -\hat{z}) \rightarrow n = (0, 1, 0_T) \]

\[ \implies \frac{d}{dt} p'_2 = e \epsilon^{s_T \sigma n \bar{n}} F_\sigma^+ \]

- total change:
  \[ \Delta p'_2 = e \int dy^- \epsilon^{s_T \sigma n \bar{n}} F^+_\sigma(y^-) \]

Set II: \[ \int dy^2_- e^{ix_2 P^+ y^2_-} [s^\sigma_T F^+_\sigma(y^2_-)] \propto \mu \cdot B \]
New experimental data: heavy flavor production

- Asymmetry for muon decay from open charm:

  - Too large error bar
  - Not able to constrain tri-gluon correlations
New experimental data: pT dependence, puzzle?

- pT dependence of asymmetry for pion production
  Kang, Qiu, in preparation

\[ A_N = \frac{N_{\text{signal}} - N_{\text{background}}}{N_{\text{signal}} + N_{\text{background}}} \]

\[ p+p \rightarrow \pi^0 + X \text{ at } \sqrt{s} = 200 \text{ GeV} \]

![Graph showing pT dependence of asymmetry for pion production](image)
New experimental data: pT dependence, puzzle?

- pT dependence of asymmetry for pion production

\[ A_N \]

\[ \text{p} + \text{p} \rightarrow \pi^0 + \text{X at } \sqrt{s} = 200 \text{ GeV} \]

\[ \langle x_f \rangle = 0.28 \]

- FPD data

\[ \langle x_f \rangle = 0.32 \]

- Sivers (E704 fit)

\[ \langle x_f \rangle = 0.37 \]

- Twist-3

\[ \langle x_f \rangle = 0.43 \]

\[ \langle x_f \rangle = 0.5 \]

\[ \langle x_f \rangle = 0.6 \]

\[ p_T, \text{ GeV/c} \]

\[ A_N \]
New experimental data: pT dependence, puzzle?

- pT dependence of asymmetry for pion production

\[ p+p \rightarrow \pi^0 + X \text{ at } \sqrt{s} = 200 \text{ GeV} \]

\[ A_N = \frac{N^A - N^n}{N^A + N^n} \]

- pT=0: \( A_N = 0 \)
- no plane any more

Kang, Qiu, in preparation
New experimental data: \( pT \) dependence, puzzle?

- **\( pT \) dependence of asymmetry for pion production**

\[ p + p \rightarrow \pi^0 + X \text{ at } \sqrt{s} = 200 \text{ GeV} \]

- \( A_N \)

  - \( \langle x_f \rangle = 0.28 \):
    - FPD data
    - Sivers (E704 fit)
    - twist–3

  - \( \langle x_f \rangle = 0.32 \):
    - very large \( pT \): approach to 0

  - \( \langle x_f \rangle = 0.37 \):
    - no plane any more

  - \( \langle x_f \rangle = 0.43 \):

  - \( \langle x_f \rangle = 0.5 \):

  - \( \langle x_f \rangle = 0.6 \):

- \( pT = 0: A_N = 0 \)

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\[ A_N \]

- \( pT \) very large: approach to 0

\[ 1/p_T \]

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New experimental data: pT dependence, puzzle?

- pT dependence of asymmetry for pion production

\[ A_N = \frac{p + p \rightarrow \pi^0 + X \text{ at } \sqrt{s} = 200 \text{ GeV}}{\langle x_f \rangle} \]

- pT=0: \( A_N = 0 \)
- no plane any more
- very large pT: approach to 0
- higher-twist, suppressed by \( \frac{1}{p_T} \)
- natural connection
- all power resummation?
New experimental data: pT dependence, puzzle?

- pT dependence of asymmetry for pion production

\[ p+p \rightarrow \pi^0 + X \text{ at } \sqrt{s} = 200 \text{ GeV} \]

1. pT=0: \( A_N = 0 \)
2. Very large pT: approach to 0
3. Higher-twist, suppressed by \( 1/p_T \)
4. Natural connection
5. All power resummation?

STAR future measurements: test high pT part

Kang, Qiu, in preparation
TMD approach

- TMD factorization applies for the process with two observed momentum scales:
  \[ Q_1 \gg Q_2 \]
  necessary for pQCD factorization to have a chance
  sensitive to parton’s transverse momentum

- Very limited processes with valid TMD factorization
  - Drell-Yan transverse momentum distribution: \( Q, q_T \)
  - Semi-inclusive DIS: \( Q, p_T \) (eg, JLab, HERMES, ...)

- How it works:
  - TMD: the quark orbital angular momentum leads to helicity flip
  - The factorizable initial (final) state interactions -- the gauge link provides the phase

Most critical test: \[ \text{Sivers}_{\text{DY}} = - \text{Sivers}_{\text{DIS}} \]
Extract Sivers function from SIDIS

\[
\begin{align*}
\text{Sivers}_u - \text{quark} &> 0 \\
\text{Sivers}_d - \text{quark} &< 0
\end{align*}
\]

- large uncertainty
- Improvement expected from JLab

\[
\begin{align*}
\pi^0 & \\
\pi^+ & \text{HERMES preliminary} \\
\pi^- & 2002-2005
\end{align*}
\]
Test of “universality”: W production at RHIC (I)

If one reconstructs W boson:

- Flavor separation
- Large asymmetry: should be able to see sign change

The only problem is that RHIC does NOT reconstruct W boson:
Test of “universality”: W production at RHIC (II)

- RHIC measures leptons decay from W boson:
  - Flavor separation
  - Asymmetry gets smaller due to dilution should still be measurable by current RHIC sensitivity

Kang, Qiu, 2009
Summary

- Single transverse-spin asymmetry is directly connected to the parton’s transverse motion
  - an excellent probe for the parton’s transverse motion

- Two complementary approaches:
  - TMD: direct $k_T$ information (two-scale observables)
  - Collinear: net spin-dependence of all $k_T$ (single-scale observables)

- For the first time, we derive the evolution equations of the twist-3 correlation functions that are responsible for generating the SSAs in the QCD collinear factorization approach
  - Consistent calculations beyond LO are now possible

- A very exciting era of transverse spin physics is coming, and the future RHIC, JLAB, JPARC, EIC and etc. experiments will play very important roles
Summary

- Single transverse-spin asymmetry is directly connected to the parton’s transverse motion
  - an excellent probe for the parton’s transverse motion

- Two complementary approaches:
  - TMD: direct kT information (two-scale observables)
  - Collinear: net spin-dependence of all kT (single-scale observables)

- For the first time, we derive the evolution equations of the twist-3 correlation functions that are responsible for generating the SSAs in the QCD collinear factorization approach
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Thank you!