(Single) Transverse Spin
Physics
-- from DIS to hadron collider

Feng Yuan
RBRC, Brookhaven National Laboratory

W. Vogelsang, F.Y., to be submitted
Outline

- Introduction
- More: RBRC Workshop on SSA (June 1-3)  
  http://quark.phy.bnl.gov/~fyuan/workshop/summer05_program.htm
- SSA in SIDIS, Physics of TMDs
- SSA at hadron colliders (RHIC)
- Summary
What is Single Spin Asymmetry?

- Consider scattering of a transversely-polarized spin-1/2 hadron \((S, p)\) with another hadron, observing a particle of momentum \(k\).

\[
\frac{d\sigma}{d\Omega} \sim S \cdot (p \times k)
\]

which produce an asymmetry \(A_N\) when \(S\) flips: **SSA**
Sample Exp. Data

- A. Bravar et al., E704, PRL77, 2626 (1996)

\[ \bar{p} + p \rightarrow \pi + X \]

FIG. 3. \( A_N \) data as a function of \( x_F \) for \( \pi^- \) and \( \pi^+ \) for \( p_T \geq 0.5 \) GeV/c. \( A_N \) data for \( \pi^0 \) in a similar \( p_T \) range are also shown [5]. The first \( \pi^- \) and \( \pi^+ \) data points are offset by \(-0.01\) and \(+0.01\) \( x_F \) units, respectively.
SSA at RHIC


\( A_N (\text{Assuming } A_{NI}^{CNI} = 0.013) \)

- \( \pi^0 \) mesons
- Total energy
- Collins
- Sivers
- Initial state twist-3
- Final state twist-3

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

- \( <\eta> = 4.1 \) (preliminary)
- \( <\eta> = 3.8 \) (PRL 92(2004)171801)

June 21, 2005
Central rapidity!!
<e>~ -0.035 => AN = -0.08 ± 0.005
+[-0.015] in 0.17 < xF < 0.32

<e>~ +0.022 => AN = +0.05 ± 0.005
+[-0.015] in 0.17 < xF < 0.32
Big SSA!

- Systematics
  - $A_N$ is significant in the fragmentation region of the polarized beam
  - $A_N$ and its sign show a strong dependence on the type of polarized beam and produced particles

- A related phenomenon: the transverse polarization of spin-1/2 particle in unpolarized hadron scattering.
Why Does SSA Exist?

- **Single Spin Asymmetry** is proportional to
  \[ \text{Im} (M_N \ast M_F) \]
  where \( M_N \) is the normal helicity amplitude
  and \( M_F \) is a spin flip amplitude

- **Helicity flip**: one must have a reaction mechanism for the hadron to change its helicity (in a cut diagram)

- **Final State Interactions (FSI)**: to generate a phase difference between two amplitudes

The phase difference is needed because the structure \( S \cdot (p \times k) \) formally violate time-reversal invariance.
**Naïve Parton Model Fails**

- If the underlying scattering mechanism is hard, the naïve parton model generates a very small SSA: *(G. Kane et al, PRL41, 1978)*
  - The only way to generate the hadron helicity-flip is through quark helicity flip, which is proportional to current quark mass $m_q$
  - To generate a phase difference, one has to have pQCD loop diagrams, proportional to $\alpha_s$
The hadron helicity flip can be generated by other mechanism in QCD

- Quark orbital angular momentum (OAM):

Beyond the naïve parton model in which quarks are collinear

**Transverse Momentum Dependent PDF!! (TMDs)**
Parton OAM and Gluons (cont.)

- A collinear gluon carries one unit of angular momentum because of its spin. Therefore, one can have a coherent gluon interaction.

Quark-gluon quark correlation function!

Qiu-Sterman Mechanism
Novel Way to Generate Phase

Some propagators in the tree diagrams go on-shell

$$\frac{1}{k^2 - m^2 + i\epsilon} = \mathcal{P} \frac{1}{k^2 - m^2} - i\pi \delta(k^2 - m^2)$$

No loop is needed to generate the phase!

Efremov & Teryaev: 1982 & 1984
Qiu & Sterman: 1991 & 1999
Comparison With Data

Qiu & Sterman, PRD59, 014004 (1999)

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RHIC & AGS USER MEETING-SPIN
SSA In Semi-inclusive Deep Inelastic Scattering (TMDs)
Inclusive and Semi-inclusive DIS

**Inclusive DIS:**
Partonic Distribution depending on the longitudinal momentum fraction

**Semi-inclusive DIS:**
Probe additional information for parton transverse distribution in nucleon
Different $P_T$ Region

- Integrate out $P_T$
  -- similar to inclusive DIS, probe int. PDF

- Large $P_T (\Lambda_{QCD})$
  -- hard gluon radiation, can be calculated from perturbative QCD,
  Polarized ->q-g-q correlations

- Low $P_T (\gg \Lambda_{QCD})$
  -- nonperturbative information (TMD): new factorization formula
A way to measure Transversity Distribution, the last unknown leading twist distribution

Collins 1993

The Novel Single Spin Asymmetries

Connections with GPDs, and Quantum Phase Space Wigner distributions

Quark Orbital Angular Momentum and Many others …
TMD Distribution: the definition

\[ Q(x, k_\perp, \mu, x_\zeta) = \frac{1}{2} \left( \frac{d\xi^-}{2\pi} e^{-i\xi^- p^+} \int \frac{d^2\vec{b}_\perp}{(2\pi)^2} e^{i\vec{b}_\perp \cdot \vec{k}_\perp} \right) \]

\[ \times \left\langle P \left| \bar{\psi}(\xi^-, 0, \vec{b}_\perp) \mathcal{L}_\nu^+(\infty; \xi^-, 0, \vec{b}_\perp) \gamma^+ \mathcal{L}_\nu(\infty; 0) \psi(0) \right| P \right\rangle \]

Gauge Invariance requires the Gauge Link

Brodsky, Hwang, Schmidt 02'
Collins 02'
Belitsky, Ji, Yuan 02'
This definition is also consistent with the QCD factorization.
Factorization

\[ F(x_B, z_h, P_{h\perp}, Q^2) = \sum_{q=u,d,s,...} e_q^2 \int d^2 k_{\perp} d^2 p_{\perp} d^2 \ell_{\perp} \times q \left( x_B, k_{\perp}, \mu^2, x_B \zeta, \rho \right) \hat{q}_h \left( z_h, p_{\perp}, \mu^2, \zeta / z_h, \rho \right) S(\ell_{\perp}, \mu^2, \rho) \times H(Q^2, \mu^2, \rho) \delta^2(z_h k_{\perp} + p_{\perp} + \ell_{\perp} - P_{h\perp}) \]

Ji, Ma, Yuan, 04’
The Factorization Applies to

- Semi-inclusive DIS (polarized and unpolarized)
- Drell-Yan at Low transverse momentum
- Di-hadron production in e+e- annihilation (extract the Collins function)
- Di-jet and/or di-hadron correlation at hadron collider (work in progress)
- Many others, …
Phenomenology

- At current stage, it is difficult to implement the full factorization approach for the phenom. Studies
- As a first step, one may neglect all higher order effects, set $S=H=1$, forget the $\zeta$ and $\rho$ in TMDs
- Back to Naïve Parton Model picture
  - Mulders & Tangelmann 96
SIDIS Cross Sections

\[ \frac{d\sigma}{dx_B dy dz_h d^2 \vec{P}_{h\perp}} = \frac{4\pi \alpha_{em}^2 s}{Q^4} \left[(1 - y + y^2/2)x_B F_{UU} \right. \\
+ (1 - y + y^2/2) \sin(\phi_h - \phi_S) |S_{\perp}| F_{siv}^{siv} \\
+ (1 - y)x_B |S_{\perp}| \sin(\phi_h + \phi_S) F_{coll}^{coll} \left. \right] , \]

\[ F_{UU} = \int q(x_B, k_{\perp}) \tilde{q}(z_h, p_{\perp}) \]

\[ F_{siv}^{siv} = \int \frac{\vec{k}_{\perp} \cdot \vec{P}_{h\perp}}{M} q_T(x_B, k_{\perp}) \tilde{q}(z_h, p_{\perp}) \]

\[ F_{coll}^{coll} = \int \frac{\vec{p}_{\perp} \cdot \vec{P}_{h\perp}}{M_{h\perp}} \delta q_T(x_B, k_{\perp}) \delta \tilde{q}(z_h, p_{\perp}) \]
Asymmetries

- Integrate over the transverse momentum

\[
d\sigma \propto 1 + A_{N}^{sivers} \sin(\phi_h - \phi_s) + A_{N}^{collins} \sin(\phi_h + \phi_s)
\]

\[
A_{N}^{sivers} \propto (1 - y + y^2/2)x_B q_T^{(1/2)}(x_B) \hat{q}(z_h)
\]

\[
A_{N}^{collins} \propto (1 - y)x_B \delta q_T(x_B) \delta \hat{q}^{(1/2)}(z_h)
\]

\[
q_T^{(1/2)}(x) = \int d^2 k_\perp \frac{|k_\perp|}{M} q_T(x_B, k_\perp)
\]
Model for the Sivers functions

- Assume only valence quark Sivers functions
  \[ u_T^{(1/2)}/u = S_u \times (1-x) \]
  \[ d_T^{(1/2)}/u = S_d \times (1-x) \]

- GRVLO for the unpolarized quark distribution
  Kretzer’s LO fragmentation function

Valence feature

Power Suppressed at x->1
Fit to HERMES Data

Sivers $A_N$ fit to $\pi^+$ and $\pi^-$ data.

- $S_u = -0.81 \pm 0.07$
- $S_d = 1.86 \pm 0.28$
- $\chi^2$/d.o.f = 1.2
Compare with COMPASS

Assume the leading hadrons are pions

HERMES large positive for $\pi^+$, and almost zero for $\pi^-$, there is strong cancellation between u and d quark Sivers function to explain the HERMES data!!
A Conjecture for Collins Function

- By summing up all hadrons, any quark Collins function vanishes,

\[ \sum_h \delta \hat{q}^h (z, k_{\perp}) \approx 0 \]

- Due to quark-hadron duality, the fragmentation function to all hadrons equals to the fragment to quark (quark+gluons) state, where the naïve T-odd effect is suppressed by quark mass

- Integrated over z with k_\perp moment\rightarrow\text{Schafer-Teryaev sumrule}
Consequence on unfavor/favor

- Isospin/charge symmetry

\[ \begin{align*}
\delta \hat{u}^+ & = \delta \hat{d}^- = \delta \hat{d}^+ = \delta \hat{u}^- = \delta \hat{q}_{favor} \\
\delta \hat{d}^+ & = \delta \hat{u}^- = \delta \hat{u}^+ = \delta \hat{d}^- = \delta \hat{q}_{unfavor} \\
\delta \hat{u}^0 & = \delta \hat{d}^0 = \delta \hat{d}^0 = \delta \hat{u}^0 = \frac{1}{2} \left[ \delta \hat{q}_{favor} + \delta \hat{q}_{unfavor} \right]
\end{align*} \]

- Under the above conjecture, neglecting Keons

\[ \delta \hat{q}_{favor} + \delta \hat{q}_{unfavor} \approx 0 \]

Support from string picture for fragmentation, Artzu
Also N. Makins’ talks
Model for Collins Functions

- Two sets of parameterizations

Set I:
\[
\delta q_{f favor}^{\pi(1/2)}(z) = C_f z (1 - z) \bar{u}^{\pi^+}(z)
\]
\[
\delta q_{un favor}^{\pi(1/2)}(z) = C_d z (1 - z) \bar{d}^{\pi^+}(z)
\]

Set II:
\[
\delta q_{f favor}^{\pi(1/2)}(z) = C_f z (1 - z) \bar{u}^{\pi^+}(z)
\]
\[
\delta q_{un favor}^{\pi(1/2)}(z) = C_d z (1 - z) \bar{d}^{\pi^+}(z)
\]

Collins function vanishes at \(z \to 0\)

\((1-z)\) comes from Collins 93’

- Transversity functions use the parameterization of Martin, Schafer, Stratmann, and Vogelsang, PRD 57(1998)
Set I Fit to HERMES

\[ C_f = 0.29 \pm 0.04 \]
\[ C_d = -0.33 \pm 0.04 \]
\[ \chi^2 / \text{d.o.f} = 0.8 \]
Compare to COMPASS

Assume the leading hadrons are pions

Discrepancy?
Set II Fit

Collins $A_N$

$\pi^+$

$\pi^-$

$C_f = 0.29 \pm 0.02$

$C_d = -0.56 \pm 0.07$

$\chi^2$/d.o.f $\equiv 0.7$
Compare to COMPASS

Assume the leading hadrons are pions
Fitted Collins Functions

Set I

Set II
Transversity functions in the fit

If we get Collins functions from other processes, e.g., $e^+e^-$, we can constrain the transversity functions!!
TMDs at RHIC

- Drell-Yan
  SSA for Drell-Yan: Sivers function has opposite sign, $q_T^{DY} = -q_T^{DIS}$, because of the gauge link changing direction.

- Di-Jet Correlation
  There is no factorization proof yet. It is likely factorizable in terms of TMDs. However, the universality of Sivers function for this case is not clear yet. We assume they are the same as DY.
SSA for Drell-Yan

Drell-Yan $A_N$ at RHIC

$5 < M_{\mu^+\mu^-} < 10 \text{GeV}$
Asym. Jet correlation probe Gluon Sivers function at RHIC

Boer, Vogelsang, PRD69:094025, 2004
Di-jet Correlation

\[ \vec{S}_\perp \times \vec{q}_\perp \approx |S_\perp| \left( \text{Sgn}(\pi - \theta) \cos \phi_1 + \sin \phi_1 \frac{|q_\perp|}{2|P_\perp|} \right) \]

\[ d\sigma \propto d\sigma_{UU} + \vec{S}_\perp \times \vec{q}_\perp d\sigma_{TU} \]

\[ = d\sigma_{UU} + \cos \phi_1 d\sigma_{TU}^{(1)} + \sin \phi_1 d\sigma_{TU}^{(2)} \]

\[ q_T^{(1/2)}(x) \quad q_T^{(1)}(x) \]
**cosφ Asymmetry**

Di-jet $A_N$ at RHIC

- $0 < y_2 < 1$
- $2 < y_2 < 3$

Gluon Sivers
Remarks on $\sin \phi$ term

- It is inclusive Di-jet cross section, depending on the azimuthal angle between the di-jet and the polarization vector $S$.
- Remember that Qiu-Sterman twist-three also contributes to the Di-jet $\sin \phi$ asymmetry.
- The connection between the above two terms needs to be further investigated.
Summary

- The simple parameterizations of the Sivers and Collins functions fit the HERMES data very well. Future data from both HERMES and COMPASS should solve the possible “discrepancy”.
- The SSAs for Drell-Yan and Di-jet correlation were predicted.
- Further studies for Di-hadron correlation including Collins asymmetry should be carried out, and also the factorization.