A New Mechanism for Generating a Single Transverse Spin Asymmetry

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The Single Transverse Spin Asymmetry (STSA)

\[ A_N \equiv \frac{d(\Delta \sigma)}{2 d\sigma_{unp}} \equiv \frac{d\sigma^{\uparrow}(k) - d\sigma^{\uparrow}(-k)}{d\sigma^{\uparrow}(k) + d\sigma^{\uparrow}(-k)} \]

- Transversely polarized hadronic collision \( A^\uparrow + B \rightarrow C + X \).
- Describes the left/right asymmetry of produced hadrons \( C \).
- \( T \)-odd correlation \( A_N \sim (\vec{S} \times \vec{p}) \cdot \vec{k} \).
- Couples hadron spin to orbital momentum distribution.
Selected STSA Data

$A_N$ vs $x_F$ in $\pi$ Production
(FNAL 1991)

$A_N$ vs $k_T$ for $\pi^0$ Production
(STAR 2008)

- **Fermilab:** Large $A_N$ (30-40%) for forward production (large $x_F$).
- **STAR:** Nonmonotonic $k_T$ dependence for forward production.
- Consistent with zero for mid, negative rapidities.
- **Contradicts naive pQCD:** $A_N$ should be energy suppressed.

+$\sqrt{s} = 20\text{GeV}$, $0.7 \leq k_T \leq 2.0\text{GeV/c}$

+$\sqrt{s} = 200\text{GeV}$

M. Sievert (OSU)
Potential Sources of STSA

STSA originates from a nontrivial $T$-odd mechanism.

3 possible sources of STSA within factorization framework:

1. Asymmetric PDF of polarized hadron. (Sivers effect)
2. Asymmetric partonic scattering. (higher-twist mechanisms)
3. Asymmetric fragmentation of polarized parton. (Collins effect)
**Color-Glass Condensate and Saturation**

\[ Y = \ln \frac{1}{x} \]

\[ Q_s^2(Y) \]

**Geometric Scaling**

- **Non-perturbative region**
- **Saturation region**

**Geometric Scaling**

- **BK/JIMWLK**
- **BFKL**
- **DGLAP**

**High energy, heavy nuclei**: gluon density saturates to classical maximum.

**Saturation momentum** \( Q_s \): fixes size of coherent color domains.

**Small-\( k_T \) gluons** are screened by average color-neutral density.

**\( Q_s \)** is a natural IR cutoff for \( k_T \): perturbative high-energy dynamics.
Wilson Lines and Dipole Degrees of Freedom

\[ D_{xy} = \frac{1}{N_c} \text{Tr} \left[ V_x V_y^\dagger \right] \quad \quad V_x = \mathcal{P} \exp \left[ i \frac{g}{2} \int dx^+ T^a A_a^-(x^+, 0, x) \right] \]

- High energy kinematics: “recoilless” eikonal propagation.
- Eikonal interactions with background field = Wilson lines.
- Wilson lines posses “crossing symmetry”: quark in \( M^* \) = antiquark in \( M \).
- Express \( d\sigma \) in terms of dipole scattering amplitudes \( D_{xy} \).
A Proxy for $p^\uparrow A$ Scattering

$$q^\uparrow + A \rightarrow (q, G, \gamma) + X$$

- Simple Wilson line: spin-independent (no STSA).
- Interaction with recoil: spin-dependent but $\frac{1}{s}$ suppressed.

Lowest-order source of spin dependence:

- Simplest spin-dependence: $O(\alpha_s)$ non-eikonal splitting $q \rightarrow q + G$.
- Splitting occurs before or after interaction with target. (Splitting during interaction is $\frac{1}{s}$ suppressed).
Leading Spin Dependence at High Energy

\[ d\sigma(k) \sim \int d^2x \, d^2y \, d^2z \, e^{-i\mathbf{k} \cdot (\mathbf{z} - \mathbf{y})} \Phi_\chi(\mathbf{z} - \mathbf{x}, \mathbf{y} - \mathbf{x}) \mathcal{I}(\mathbf{x}, \mathbf{y}, \mathbf{z}) \]

\[ \mathcal{I} \xrightarrow{\text{large } -N_c} D_{zy} + D_{uw} - D_{zx}D_{xw} - D_{ux}D_{xy} \]

- Wave function \( \Phi_\chi = \Phi_{\text{unp}} + \chi \Phi_{\text{pol}} \) links spin dependence with parity.
- Interaction \( \mathcal{I} = \mathcal{I}_{\text{symm}} + \mathcal{I}_{\text{anti}} \) can be decomposed by time reversal symmetry: \( \mathbf{k} \rightarrow -\mathbf{k} \) or quark ↔ antiquark.
The Odderon Drives the Asymmetry

- STSA generated by spin-dependent splitting $\Phi_{pol}$ and asymmetric scattering $\mathcal{I}_{anti}$.

$$d(\Delta \sigma) \sim \mathcal{F} \cdot \mathcal{T} \cdot [\Phi_{pol} \otimes \mathcal{I}_{anti}]$$

$$\mathcal{I}_{anti} = i(O_{zy} + O_{uw} - O_{zx} S_{xw} - O_{ux} S_{xy} - S_{zx} O_{xw} - S_{ux} O_{xy})$$

- Asymmetric scattering driven by $T$-odd, $C$-odd “odderon” interaction $O_{xy}$.

- Sensitive to dipole orientation; couples to gradients of density.
Terms with only $O_{xy}$ average out to zero after integration.

**$(q,G,\gamma)$ production: same wave function, different interactions**

- $I_{anti}^{(q)} = i(O_{zy} + O_{uw} - O_{zx}S_{xw} - O_{ux}S_{xy} - S_{zx}O_{xw} - S_{ux}O_{xy})$
- $I_{anti}^{(G)} = i(O_{uw} - S_{xz}O_{zw} - O_{xz}S_{zw} - S_{uy}O_{yx} - O_{uy}S_{yx})$
- $I_{anti}^{(\gamma)} = i(O_{uw} - O_{xw} - O_{ux})$

- Nonzero asymmetry arises from interference of $T$, $C$-even/odd scattering before/after splitting.

- Our mechanism does not contribute to STSA for prompt photons.
Approximating the Integrals (Quark Production)

\[ \frac{k^+}{p^+} = 0.9, 0.7, 0.6, 0.5 \]

(Parameters chosen to mimic a proton target.)

- \( A_N \) increases with increasing \( x_F \) (until \( x_F \approx 1 \)).
- \( A_N \) is non-monotonic in \( k_T \) (possesses nodes).
- \( A_N \) peaks at some average saturation scale \( \langle Q_s \rangle \).
- \( A_N \sim \frac{1}{k_T^9} \) at large \( k_T \) (higher-twist behavior).
- \( A_N \sim A^{-7/6} \): suppressed for central collisions / heavy nuclei.
- \( A_N \sim |\nabla T|^2 \): sensitive to edge effects (cutoff dependence).
In the high-energy/CGC framework, the leading STSA occurs through a \( T, C \)-odd scattering mechanism (Odderon).

Only the interference of odd + even scattering survives event averaging.

→ Does not contribute to prompt photon STSA.

Increases with \( x_F \) and innately non-monotonic (nodes).

Couples to density gradients; dominated by peripheral collisions.

Complements other nonperturbative mechanisms: Sivers, Collins

May provide a missing piece of the STSA puzzle.
Extra Slides: New $\sqrt{s} = 500\, \text{GeV}$ Data

STAR Run 11 preliminary data

- Still increases with $x_F$.
- $p_T$ dependence is almost flat...?
Larger $A$ smoothes out density gradients.

For $k_T \sim Q_s$, $A_N \sim A^{-7/6}$

Strongest for peripheral collisions; suppressed at central collisions.
Brodsky, Hwang, and Schmidt (Phys. Lett. B, 2002): “Spectator interactions” with on-shell intermediate state can produce STSA.

High-energy analog: $T$-odd wave function + $T$, $C$-even interaction

Can be of the same order as odderon-driven STSA.