A New Mechanism for Generating a Single Transverse Spin Asymmetry

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The Single Transverse Spin Asymmetry (STSA)

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

- 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.
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.
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

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

\[ D_{xy} = \frac{1}{N_c} \text{Tr} \left[ V_x V_y^\dagger \right] \]

\[ V_x = \mathcal{P} \exp \left[ i \frac{g}{2} \int dx^+ T^a A^a_- (x^+, 0, x) \right] \]

- High energy kinematics: “recoilless” eikonal propagation.
- Eikonal interactions with background field = Wilson lines.
- Wilson lines possess “crossing symmetry”: quark in \( \mathcal{M}^* \) = antiquark in \( \mathcal{M} \).
- 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: \textit{spin-independent} (no STSA).
- Interaction with recoil: \textit{spin-dependent} but $\frac{1}{s}$ suppressed.

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

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

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

- 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: \( k \rightarrow -k \) or quark \( \leftrightarrow \) antiquark.
The Odderon Drives the Asymmetry

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

$$d(\Delta \sigma) \sim \mathcal{F.T.}[\Phi_{pol} \otimes I_{anti}]$$

$$S_{xy} = \frac{1}{2} (D_{xy} + D_{yx})$$

$$O_{xy} = \frac{1}{2i} (D_{xy} - D_{yx})$$

$$I_{anti} = i(O_{zy} + O_{uw} - O_{zx}S_{xw} - O_{ux}S_{xy} - S_{zx}O_{xw} - S_{ux}O_{xy})$$

- Asymmetric scattering driven by $T$-odd, $C$-odd “odderon” interaction $O_{xy}$.
- Sensitive to dipole orientation; couples to gradients of density.
Quark, Gluon, and Prompt Photon Production

Terms with only $O_{xy}$ average out to zero after integration.

$$(q,G,\gamma) \text{ production: same wave function, different interactions}$$

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

- 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 \( \langle Q_s \rangle \).
- \( A_N \approx \frac{1}{k_T^9} \) at large \( k_T \) (higher-twist behavior).
- \( A_N \approx A^{-7/6} \): suppressed for central collisions / heavy nuclei.
- \( A_N \approx |\nabla T|^2 \): 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 $\sqrt{s} = 500 GeV$ 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.

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

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