A New Mechanism for Generating a Single Transverse Spin Asymmetry

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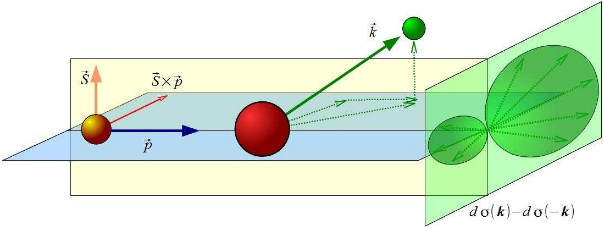
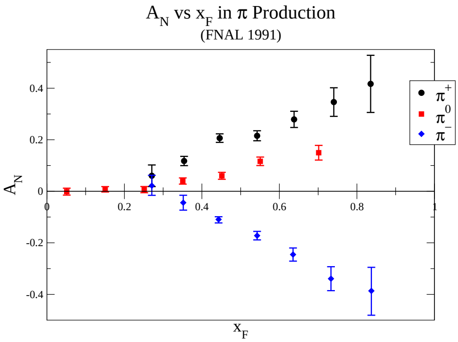
The Single Transverse Spin Asymmetry (STSA)



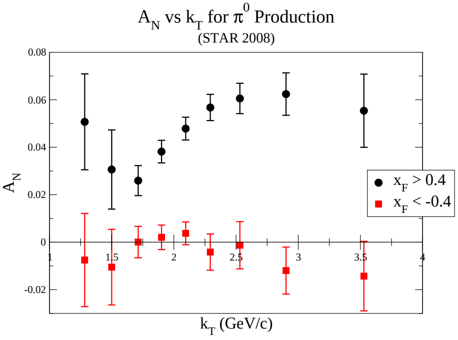
$$A_N \equiv \frac{d(\Delta\sigma)}{2\, d\sigma_{unp}} \equiv \frac{d\sigma^{\uparrow}(\mathbf{k})-d\sigma^{\uparrow}(-\mathbf{k})}{d\sigma^{\uparrow}(\mathbf{k})+d\sigma^{\uparrow}(-\mathbf{k})} = \frac{d\sigma^{\uparrow}(\mathbf{k})-d\sigma^{\downarrow}(\mathbf{k})}{d\sigma^{\uparrow}(\mathbf{k})+d\sigma^{\downarrow}(\mathbf{k})}$$

- 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



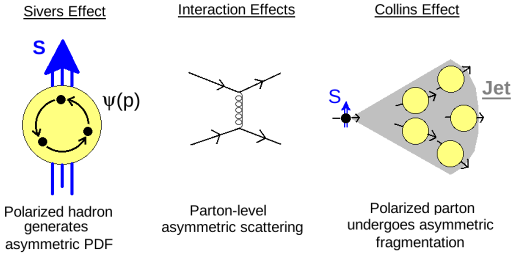
$\sqrt{s} = 20GeV, \quad 0.7 \leq k_T \leq 2.0GeV/c$



$\sqrt{s} = 200GeV$

- 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

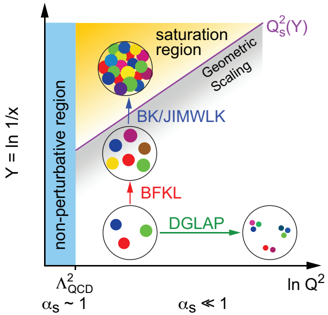


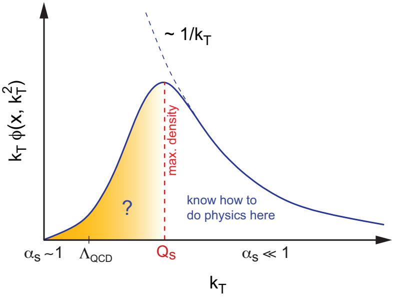
- STSA originates from a nontrivial T-odd mechanism.

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

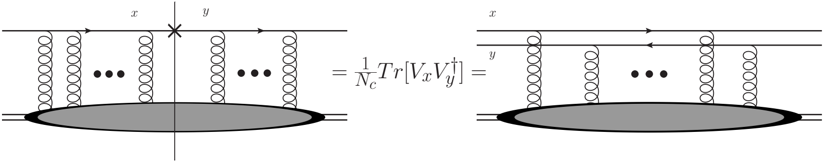




$$Q_s \sim A^{1/3} s^{\lambda} \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda}$$

- 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

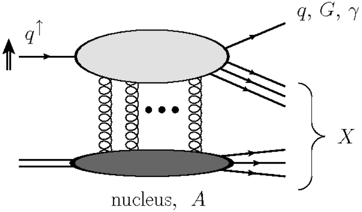


$$D_{xy} = \frac{1}{N_c} \mathrm{Tr}\left[V_x V_y^\dagger\right] \qquad V_x = \mathcal{P} \exp\left[i\frac{g}{2}\int dx^+ T^a A^{a-}(x^+, 0, \mathbf{x})\right]$$

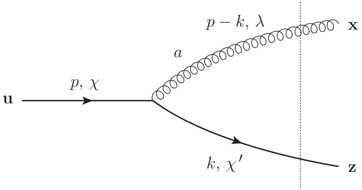
- High energy kinematics: “recoilless” eikonal propagation.
- Eikonal interactions with background field = Wilson lines.
- Wilson lines posses “crossing symmetry”: quark in $\mathcal{M}^* =$ antiquark in $\mathcal{M}$.
- Express $d\sigma$ in terms of dipole scattering amplitudes D_{xy}.

A Proxy for $p^{\uparrow}A$ Scattering

$q^{\uparrow} + A \to (q, G, \gamma) + X$



$q \to q + G$ wave function

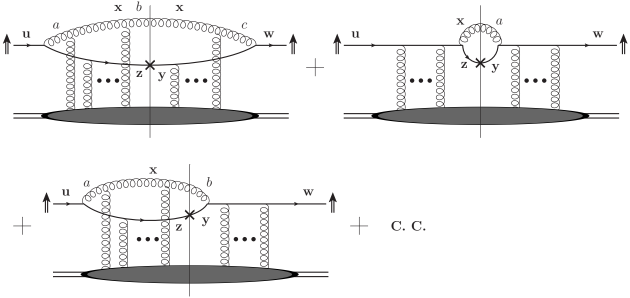


- Simple Wilson line: spin-independent (no STSA).
- Interaction with recoil: spin-dependent but $\frac{1}{s}$ suppressed.

Lowest-order source of spin dependence:

- Simplest spin-dependence: $\mathcal{O}(\alpha_s)$ non-eikonal splitting $q \to q + G$.
- Splitting occurs before or after interaction with target.
  (Splitting during interaction is $\frac{1}{s}$ suppressed).

Leading Spin Dependence at High Energy

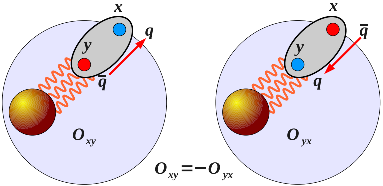


$$d\sigma(\mathbf{k}) \sim \int d^2x\, d^2y\, d^2z\, e^{-i\mathbf{k}\cdot(\mathbf{z}-\mathbf{y})}\, \Phi_\chi(\mathbf{z}-\mathbf{x}, \mathbf{y}-\mathbf{x})\, \mathcal{I}(\mathbf{x}, \mathbf{y}, \mathbf{z})$$

$$\mathcal{I} \xrightarrow{\text{large}-\text{N}_c} D_{zy} + D_{uw} - D_{zx} D_{xw} - D_{ux} D_{xy}$$

- Wave function $\Phi_\chi = \Phi_{unp} + \chi \Phi_{pol}$ links spin dependence with parity.
- Interaction $\mathcal{I} = \mathcal{I}_{symm} + \mathcal{I}_{anti}$ can be decomposed by time reversal symmetry: $\mathbf{k} \to -\mathbf{k}$ or quark $\leftrightarrow$ antiquark.

The Odderon Drives the Asymmetry



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

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

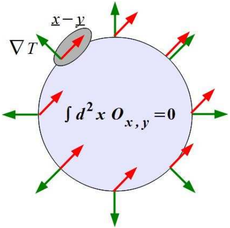
$$S_{xy} = \frac{1}{2}(D_{xy} + D_{yx})$$

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

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

- Asymmetric scattering driven by T-odd, C-odd "odderon" interaction O_{xy}.
- Sensitive to dipole orientation; couples to gradients of density.

Quark, Gluon, and Prompt Photon Production



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

(q,G,γ) production: same wave function, different interactions

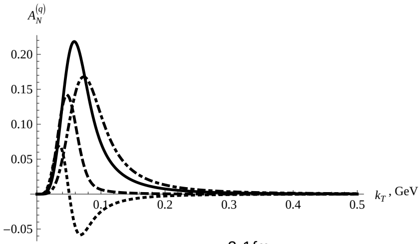
$$\mathcal{I}^{(q)}_{anti} = i\left(O_{zy} + O_{uw} - O_{zx}S_{xw} - O_{ux}S_{xy} - S_{zx}O_{xw} - S_{ux}O_{xy}\right)$$
$$\mathcal{I}^{(G)}_{anti} = i\left(O_{uw} - S_{xz}O_{zw} - O_{xz}S_{zw} - S_{uy}O_{yx} - O_{uy}S_{yx}\right)$$
$$\mathcal{I}^{(\gamma)}_{anti} = i\left(O_{uw} - O_{xw} - O_{ux}\right)$$

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

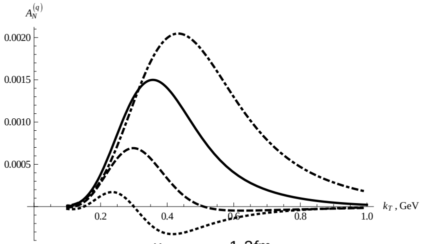
- Our mechanism does not contribute to STSA for prompt photons.

Approximating the Integrals (Quark Production)

$\frac{k^+}{p^+} = 0.9, 0.7, 0.6, 0.5$ (Parameters chosen to mimic a proton target.)



$x_{T,max} = 2.1 fm$



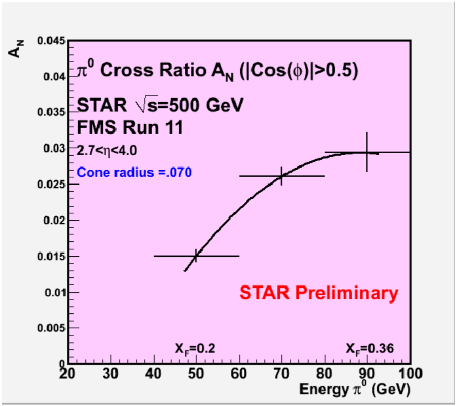
$x_{T,max} = 1.3 fm$

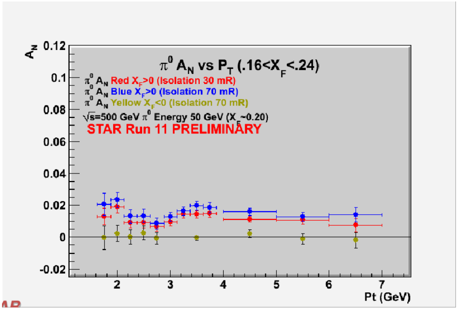
- A_N increases with increasing x_F (until $x_F \approx 1$).
- A_N is non-monotonic in k_T (possesses nodes).
- A_N peaks at some average saturation scale $\langle Q_s \rangle$.
- $A_N \sim \frac{1}{k_T^9}$ at large k_T (higher-twist behavior).
- $A_N \sim A^{-7/6}$: suppressed for central collisions / heavy nuclei.
- $A_N \sim |\nabla T|^2$: sensitive to edge effects (cutoff dependence).

Summary: A New Mechanism for STSA

- 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.
  $\longrightarrow$ 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

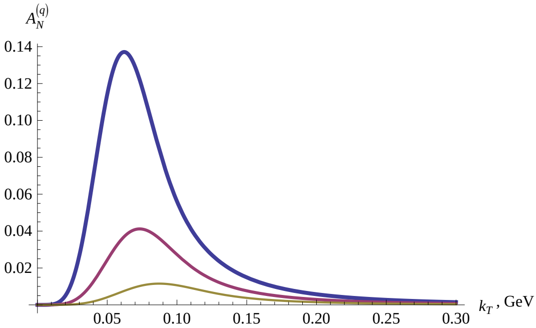




STAR Run 11 preliminary data

- Still increases with x_F.
- p_T dependence is almost flat...?

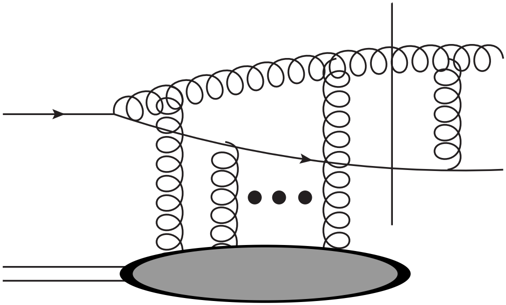
Extra Slides: Centrality Dependence



$R = 1fm, 1.4fm, 2fm$ $\quad \frac{k^+}{p^+} = 0.7$ $\quad x_{T,max} = 2.4fm$

- 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.

Extra Slides: BHS Mechanism



- 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.