“Transversity” Correlations Azimuthal and Single Spin Asymmetries

Leonard Gamberg*
Division of Science, Penn State Berks

Second Joint JPS-DNP APS Meeting
Maui, Hawaii 2005
Mini-Symposium 14e: Orbital Motion of Quarks in Hard Scattering Processes

• Remarks TSSA: Correlations btwn. intrinsic $k_\perp$ and transverse spin $S_T$ properties of hadrons and quarks in QCD
★ “Novel” Transversity Properties in Hard Scattering
★ Reaction Mechanism: “$T$-odd” Structure and Fragmentation Functions role in TSSA and AA
★ Estimates of Collins and Sivers Asymmetries
★ Double $T$-odd $\cos 2\phi$ asymmetry: SIDIS & DRELL-YAN
• Conclusions

*G. R. Goldstein, Tufts Univ., K.A. Oganessyan Financial District NYC, and D.S. Hwang Sejong Univ, Korea
JPS-DNP Maui, 18-22 Sept. 2005
Transverse SSA (TSSA) and AZIMUTHAL ASYMMETRIES (AA)

- **LARGE TSSAS OBSERVED**

\[
A_N = \frac{d\sigma_p^\uparrow p \rightarrow \pi X - d\sigma_p^\downarrow p \rightarrow \pi X}{d\sigma_p^\uparrow p \rightarrow \pi X + d\sigma_p^\downarrow p \rightarrow \pi X}
\]

L-R asymmetry of \( \pi \) production and \( A_N \) for \( \pi_0 \) production at STAR: PRL 2004

\[ P_\Lambda \text{ in } p-p \text{ scattering from Fermi Lab} \]

\[
P_\Lambda = \frac{d\sigma_{pp}^{\Lambda \uparrow} X - d\sigma_{pp}^{\Lambda \downarrow} X}{d\sigma_{pp}^{\Lambda \uparrow} X + d\sigma_{pp}^{\Lambda \downarrow} X}
\]

Transverse SSA (TSSA) and AZIMUTHAL ASYMMETRIES (AA)

★ Colinear approximation

TSSA vanishingly small at large scales and leading order $\alpha_s$

Generically,

$$|\perp/T>=\frac{1}{\sqrt{2}}(|+>\pm i|->) \Rightarrow A_N = \frac{d\hat{\sigma} \perp - d\hat{\sigma} \top}{d\hat{\sigma} \perp + d\hat{\sigma} \top} \sim \frac{2 \text{Im } f^* + f^-}{|f|^2 + |f^-|^2}$$

★ Requires *helicity flip* as well as real/tive phase btwn helicity amps

• At partonic level massless QCD conserves helicity Born amplitudes are real!

★ Interference btwn loops-tree level Kane, Repko, PRL:1978 yield $A_N \sim m_q \alpha_s/\sqrt{s}$


See talks of Koike
Inclusive $\Lambda$ production ($pp \to \Lambda^\uparrow X$)

$$P_\Lambda = \frac{d\sigma^{pp \to \Lambda^\uparrow X} - d\sigma^{pp \to \Lambda^\downarrow X}}{d\sigma^{pp \to \Lambda^\uparrow X} + d\sigma^{pp \to \Lambda^\downarrow X}}$$

- Inclusive $\Lambda$ production ($pp \to \Lambda^\uparrow X$) PQCD contributions calculated
  Dharmartna & Goldstein PRD 1990
  $P_\Lambda$ goes like $m_q \alpha_s / \sqrt{s}$ as predicted $m_q$ is the strange quark mass
Helicity Flips Accommodated in Hard Scattering, Through “Transversity”

\[ \text{Drell-Yan } p_\perp p_\perp \Rightarrow l^+ l^- X \text{ (2 in the initial)} \]
\[ \text{SIDIS } l \ p_\perp \Rightarrow l' \ h \ X \text{ (1 in initial 1 in final)} \]

★ **DY:** Ralston and Soper NPB:1979 encountered double transverse spin asymmetry

\[
A_{DY}^{TT} = \frac{2 \sin^2 \theta \cos(\phi_1 + \phi_2) \sum_a e_a^2 h_1^a(x) \bar{h}_1^a(x)}{1 + \cos^2 \theta} \frac{\sum_a e_a^2 f_1^a(x) \bar{f}_1^a(x)}{\sum_a e_a^2 f_1^a(x) \bar{f}_1^a(x)}
\]

\[ h_1(x) \] probability to find quark with spin polarized along transverse spin direction minus oppositely polarized case
SIDIS: Jaffe and Ji PRL:1993 encountered at twist three level double spin asymmetry
Estimate, Gamberg, Hwang, Oganessyan PLB:2004

\[ A_{LT} = \frac{A_{LT}}{[1 + (1-y)^2]} f_1(x) D_1(z) \]

Analogous process in Drell-Yan \( \pi P \rightarrow \mu^+ \mu^- X \)
Ji PLB:1992
“$T$-Odd” (or $A_T$) Correlations: Beyond Co-linearity

- TSSA indicative $T$-odd correlations among transverse spin and momenta e.g. $P P^\perp \rightarrow \pi X \quad S_T \cdot (P \times k^\perp)$

- If sensitive to $k^\perp$ corresponds to intrinsic quark momenta, effect associated with non-perturbative transverse momentum distribution functions
  Soper, PRL:1979: $\int d k^\perp \mathcal{P}(k^\perp, x) = f(x)$

- Such a correlation to account a left-right transverse SSA
  Sivers: PRD 1990 in inclusive $\pi$ production

\[ \begin{array}{c}
\text{P} \\
\downarrow \\
S_T \\
\end{array} \quad \begin{array}{c}
k^\perp \\
\end{array} \quad \begin{array}{c}
P \\
\end{array} \]

- Soon after Collins NPB 1993 proposed $T$-odd correlation of transversely polarized fragmenting quark: TSSA in lepto-production $\ell \not{p} \rightarrow \ell' \pi X$

- Initial-Final state effect: $s_T \cdot (p \times P_{h^\perp})$, where $s_T$ is the spin of fragmenting quark, $p$ is quark momentum and $P_{h^\perp}$ is transverse momentum produced pion
**T-Odd Correlations: Beyond Co-linearity**


\[
\frac{d\sigma^{\ell+N \rightarrow \ell'+h+X}}{dx dy dz d^2 P_{h\perp}} = \frac{M \pi \alpha'^2 y}{2Q^4 z} L_{\mu\nu} \mathcal{W}^{\mu\nu}
\]

Hadronic Tensor

\[
2M \mathcal{W}^{\mu\nu}(q, P, P_h) = \int d^2 p_T d^2 k_T \delta^2(p_T + q_T - k_T) \text{Tr}[\Phi(x_B, p_T)\gamma^\mu \Delta(z_h, k_T)\gamma^\nu] + (q \leftrightarrow -q, \mu \leftrightarrow \nu)
\]
Color Gauge Invariance Built into & Factorized QCD at “tree level” - Wilson Line & T-Odd Contributions to QCD Processes

- Gauge Invariant Distribution and Fragmentation Functions


Sub-class of loops in eikonal limit (soft gluons) sum up to to yeild color gauge invariant hadronic tensor factorized into the distribution and fragmentation operators

\[
\Phi(p, P) = \int \frac{d^3 \xi}{2(2\pi)^3} e^{iP: \xi} \langle P | \overline{\psi}(-, \xi_\perp) G^{+}_{\xi_\perp, \infty} | X \rangle \langle X | G_{0, \infty} \psi(0) | P \rangle |_{\xi_\perp = 0}
\]

\[
\Delta(k, P_h) = \int \frac{d^3 \xi}{4\pi^3} e^{ik: \xi} \langle 0 | G_{\xi_\perp, -\infty} \psi(\xi) | X; P_h \rangle \langle X; P_h | \overline{\psi}(0) G^{+}_{0, -\infty} | 0 \rangle |_{\xi_\perp = 0}
\]

\[
\mathcal{W}^{\mu \nu}(q, P, P_h) = \frac{1}{2M} \int d^2 p_T d^2 k_T \delta^2(p_T + q_T - k_T) Tr \left[ \Phi(x_B, p_T) \gamma^\mu \Delta(z_h, k_T) \gamma^\nu \right] + (q \leftrightarrow -q, \mu \leftrightarrow \nu)
\]
More recently Ji, Ma, Yuan: 2004 building on work of Collins-Soper NPB: 81, extended factorization theorems to 1-loop and beyond

Suggestions of Universality & Collins and Metz: 2005
• We focus on T-odd Distribution Functions: Transversity Properties of quarks in Hadrons Boer, Mulder, PRD 1998

\[
\Delta(z, k_T) = \frac{1}{4} \{ D_1(z, z k_T) n_+ + H_1^\perp(z, z k_T) \sigma^{\alpha\beta} k_T^\alpha n_-^\beta + D_{1T}^\perp \epsilon_{\mu\nu\rho\sigma} \gamma^\mu n_-^\nu k_T^\rho S_{hT}^\sigma + \cdots \},
\]

\[
\Phi(x, p_T) = \frac{1}{2} \{ f_1(x, p_T) n_+ + h_1(x, p_T) \sigma^{\alpha\beta} p_T^\alpha n_+^\beta + f_{1T}(x, p_T) \epsilon_{\mu\nu\rho\sigma} \gamma^\mu n_+^\nu p_T^\rho S_{T}^\sigma + \cdots \}.
\]
Provides source of T-Odd Contributions to TSSA and Azimuthal Asymmetries in SIDIS

\[ d\sigma_{\lambda,S} \propto f_1 \otimes D_1 + \frac{k_T}{Q} f_1 \otimes D_1 \cdot \cos \phi \]
\[ + \left[ \frac{k_T^2}{Q^2} f_1 \otimes D_1 + h_1 \otimes H_1^\perp \right] \cdot \cos 2\phi \]
\[ + |S_T| \cdot h_1 \otimes H_1^\perp \cdot \sin(\phi + \phi_S) \quad \text{Collins} \]
\[ + |S_T| \cdot f_{1T}^\perp \otimes D_1 \cdot \sin(\phi - \phi_S) \quad \text{Sivers} \]
\[ + \ldots \]

And T-Odd Contributions to TSSA and Azimuthal Asymmetries in

Drell Yan Boer PRD:1999,
Rescattering-ISI/FSI $T$-Odd Contributions to Asymmetries

**PLB: 2002** Brodsky, Hwang, and Schmidt demonstrate rescattering of a gluon could produce the necessary phase leading to nonzero SSAs at *Leading Twist*

• Ji, Yuan & Belitsky **PLB: 2002, NPB 2003** describe effect in terms of gauge invariant distribution functions

\[
\Rightarrow \langle P | \overline{\psi}(\xi^-, \xi^\perp) G_{[\xi, \infty]}^\dagger | x \rangle \langle x | G_{[0, \infty]} \psi(0) | P \rangle |_{\xi^+=0}
\]

\[
G_{[\xi, \infty]} = G_{[\xi^T, \infty]} G_{[\xi^-, \infty]}, \quad \text{where} \quad G_{[\xi^-, \infty]} = \mathcal{P} \exp(-ig \int_{\xi^-}^{\infty} d\xi^- A^+)
\]

• Demonstrates that BHS calculated Sivers Function $f_{1T}^\perp(x, k^\perp)|_{\text{SDIS}}$

In Singular gauge, $A^+ = 0$, effect remains

• **Collins, PLB: 2002**, modifies earlier claim of trivial Sivers Effect

\[
f_{1T}^\perp(x, k^\perp)|_{\text{SDIS}} = -f_{1T}^\perp(x, k^\perp)|_{\text{DY}}
\]
SIDIS and Transversity Properties at Leading Twist


Transversity can be measured via azimuthal asymmetry in the fragmenting hadron’s momentum, Collins effect:

\[ P_{h\perp} \] - hadron transverse momentum

\[ \phi \] - azimuth between \[ [k, q] \] and \[ [P_{h}, q] \] planes

\[ \phi_s \] - azimuth of the target spin vector

One considers cross sections differential in transverse momentum: SSA not surpressed by inverse powers of the hard scale.

\[
\left\langle \frac{P_{h\perp}}{M_\pi} \sin(\phi + \phi_s) \right\rangle_{UT} = \frac{\int d\phi_s \int d^2P_{h\perp} \frac{P_{h\perp}}{M_\pi} \sin(\phi + \phi_s) \left( d\sigma^{\uparrow} - d\sigma^{\downarrow} \right)}{\int d\phi_s \int d^2P_{h\perp} \left( d\sigma^{\uparrow} + d\sigma^{\downarrow} \right)}
\]

\[
= |S_T| \frac{2(1 - y) \sum_q e_q^2 h_1(x) z H_1^{\perp(1)}(z)}{(1 + (1 - y)^2) \sum_q e_q^2 f_1(x) D_1(z)}
\]
Sivers Asymmetry in SIDIS

- Probes the probability that for a transversely polarized target, pions are produced asymmetrically about the transverse spin vector:

(Sivers PRD: 1990, Anselmino & Murgia PLB: 1995 ...)

Hadron helicity flip furnished by orbital angular momentum, quarks have \( k_\perp \)

\[
\langle \frac{|P_{h\perp}|}{M} \sin(\phi - \phi_S) \rangle_{UT} = |S_T| \frac{(1 + (1 - y)^2) \sum_q e_q^2 f_{1T}^{\perp(1)}(x) z D_1^q(z)}{(1 + (1 - y)^2) \sum_q e_q^2 f_1(x) D_1(z)},
\]

Reaction Mechanism explained as FSI

☆ See Star and HERMES Data
**cos** 2\(\phi\) **Asymmetry** Generated by ISI & FSI thru Gauge link


\[
A_{UU}^{\cos(2\phi)} = \left\langle \frac{|P_{h\perp}|}{MM_h} \cos 2\phi \right\rangle_{UU} \\
= \frac{8(1 - y) \sum_q e_q^2 h_1^{(1)}(x, Q^2) z^2 H_1^{(1)q}(z, Q^2)}{(1 + (1 - y)^2) \sum_q e_q^2 f_1^q(x, Q^2) D_1^q(z, Q^2)}
\]

\[
\frac{d\sigma}{dx dy dz d^2P_{\perp}} \propto f_1 \otimes D_1 + \frac{k_T}{Q} f_1 \otimes D_1 \cdot \cos \phi + \left[ \frac{k_T^2}{Q^2} f_1 \otimes D_1 + h_1^\perp \otimes H_1^\perp \right] \cdot \cos 2\phi
\]


JPS-DNP Maui, 18-22 Sept. 2005
Rescattering Mechanism to Generate $T$-Odd Function $h_1^\perp$


- $h_1^\perp$ Naturally defined from gauge invariant TMPDF(s)
- Apply "eikonal Feynman rules", (Collins, Soper, NPB: 1982)

$$
\Phi[\sigma^\perp + \gamma_5]_{h_1^\perp} = \frac{1}{2} \int dp^- \text{Tr} \left( i\sigma^\perp + \gamma_5 \Phi \right) = \frac{e^+ - \frac{1}{4} k^\perp \gamma_5^\perp}{M} h_1^\perp(x, k_\perp)
$$

$h_1^\perp(x, k_\perp)$, represents, number density transversely polarized quarks in an unpolarized nucleons nucleons-complementary to $f_{1T}^\perp(x, k_\perp)$.
Estimates of T-odd Contribution in SIDIS and Azimuthal Asymmetries Drell Yan (GSI program)

\[ \cos 2\phi \text{ Asymmetry} \]

- The spectator model used in previous rescattering calculations assumes point-like nucleon-quark-diquark vertex, leads to logarithmically divergent, asymmetries

Goldstein, L. Gamberg, ICHEP 2002;
Gamberg, Goldstein, Oganessyan PRD 2003; Boer, Brodsky, Hwang, PRD: 2003(Drell-Yan)

\[
h_{\perp}^{T}(x, k_{\perp}) = f_{1T}(x, k_{\perp}) = \frac{g^{2}e_{1}e_{2}}{4\pi(2\pi)^{3}} \frac{(1 - x)(m + xM)}{\Lambda(k_{\perp}^{2})} \frac{M}{k_{\perp}^{2}} \ln \frac{\Lambda(k_{\perp}^{2})}{\Lambda(0)}
\]

\[
\Lambda(k_{\perp}^{2}) = k_{\perp}^{2} + x(1 - x) \left( -M^{2} + \frac{m^{2}}{x} + \frac{x^{2}}{1 - x} \right)
\]

- Asymmetry involves weighted function

\[
h_{\perp}^{(1)}(x) \equiv \int d^{2}k_{\perp} \frac{k_{\perp}^{2}}{2M^{2}} h_{\perp}(x, k_{\perp}) \text{ diverges}
\]
Gaussian Distribution in $k_\perp$

Log divergence addressed by approximating the transverse momentum dependence of the quark-nucleon-vertex by a Gaussian distribution in $k_\perp^2$,


$$\langle n|\psi(0)|P\rangle = \left(\frac{i}{k' - m}\right)\gamma(k_\perp^2)U(P, S), \quad b \equiv \frac{1}{\langle k_\perp^2 \rangle}$$

where \(\gamma(k_\perp^2) = \mathcal{N}e^{-bk_\perp^2}\).

\(U(P, S)\) nucleon spinor, and quark propagator comes from untruncated quark line

$$h_\perp^2(x, k_\perp) = \frac{e_1 e_2 g^2}{2(2\pi)^4} \frac{b^2 (m + xM)(1 - x)}{\Lambda(k_\perp^2)} \frac{1}{k_\perp} \mathcal{R}(k_\perp^2, x) \quad (1)$$

with

$$\mathcal{R}(k_\perp^2, x) = \exp\left(-2b(k_\perp^2 - \Lambda(0))\right) \left(\Gamma(0, 2b\Lambda(0)) - \Gamma(0, 2b\Lambda(k_\perp^2))\right)$$

- \(\lim < k_\perp^2 > \to \infty\) width goes to infinity, regain log result
Boer-Mulders and Unpolarized Structure Function

\[ f(x) = \frac{g^2}{(2\pi)^2} \frac{b^2}{\pi^2} (1 - x) \cdot \left\{ \frac{(m + xM)^2 - \Lambda(0)}{\Lambda(0)} - 2b \left( (m + xM)^2 - \Lambda(0) \right) - 1 \right\} e^{2b\Lambda(0)\Gamma(0, 2b\Lambda(0))} \]

- Normalization, \( \int_0^1 u(x) = 2 \)
- \( \int_0^1 d(x) = 1 \)
- Black curve- \( xu(x) \)
- Purple curve - \( xu(x) \) from GRV
- Red curve \( xh_{1\perp}(1/2)(u) \)
Pion Fragmentation Function

\[
D_1(z) = \frac{N_f^2 f_{qq}^2}{4(2\pi)^2} \frac{1}{z} \left( 1 - z \right) \left\{ \frac{m^2 - \Lambda'(0)}{\Lambda'(0)} - \left[ 2b' \left( m^2 - \Lambda'(0) \right) - 1 \right] e^{2b'\Lambda'(0)} \Gamma(0, 2b'\Lambda'(0)) \right\},
\]

which, multiplied by \(z\) at \(<k_{\perp}^2> = (0.5)^2\) GeV\(^2\) and \(\mu = m\), estimates the distribution of Kretzer, PRD: 2000.
Gauge Link-Pole Contribution to T-Odd Collins Function

Gamberg, Goldstein, Oganessyan PRD68, 2003

Consistent with BPM 2003 “pole contribution” We evaluate the projection \( \Delta [i \sigma^\perp \gamma_5] \), which results in the leading twist, contribution to \( T \)-odd pion fragmentation

\[
H_1^\perp (z, k^\perp) = \frac{N_f^2 f^2 g^2}{(2\pi)^4} \frac{1}{4z} \frac{(1 - z)}{z} \frac{\mu}{\Lambda'(k^2_\perp)} \frac{M_\pi}{k^2_\perp} R(z, k^2_\perp)
\]

where, \( \Lambda'(k^2_\perp) = k^2_\perp + \frac{1 - z}{z^2} M^2_\pi + \frac{\mu^2}{z} - \frac{1 - z}{z} m^2 \)
Collins Asymmetry

Gamberg, Goldstein, Oganessyan PRD 2003: updated  For the HERMES kinematics

$1 \text{ GeV}^2 \leq Q^2 \leq 15 \text{ GeV}^2$, $4.5 \text{ GeV} \leq E_\pi \leq 13.5 \text{ GeV}$, $0.2 \leq x \leq 0.41$, $0.2 \leq z \leq 0.7$, $0.2 \leq y \leq 0.8$, $< P_{h\perp}^2 >= 0.25 \text{ GeV}^2$

$$\langle \frac{P_{h\perp}}{M_\pi} \sin(\phi + \phi_s) \rangle_{UT} = |S_T| \frac{2(1 - y) \sum_q e_q^2 h_1(x) z H_1^{1(1)}(z)}{(1 + (1 - y)^2) \sum_q e_q^2 f_1(x) D_1(z)}.$$

Data from A. Airapetian et al, PRL94, 2005
Estimates for Sivers Asymmetry

Data from A. Airapetian et al. PRL94,2005

\[
\langle \frac{|P_{h\perp}|}{M} \sin(\phi - \phi_S) \rangle_{UT} = \frac{\int d^2 P_{h\perp} \frac{|P_{h\perp}|}{M} \sin(\phi - \phi_S) \, d\sigma}{\int d^2 P_{h\perp} \, d\sigma} = \frac{(1 + (1 - y)^2) \sum_q e_q^2 f_1^{\perp(1)}(x) z D_1^{q}(z)}{(1 + (1 - y)^2) \sum_q e_q^2 f_1(x) D_1(z)},
\]
Double T-odd $\cos 2\phi$ asymmetry

Transversity of quarks inside an unpolarized hadron, and $\cos 2\phi$ asymmetries in unpolarized semi-inclusive DIS

\[ \left\langle \frac{|P_{h\perp}^2|}{MM_h} \cos 2\phi \right\rangle_{UU} = \frac{\int d^2 P_{h\perp} \frac{|P_{h\perp}^2|}{MM_h} \cos 2\phi \, d\sigma}{\int d^2 P_{h\perp} \, d\sigma} = \frac{8(1 - y) \sum_q e_q^2 h_1^{(1)}(x) z^2 H_1^{(1)}(z)}{(1 + (1 - y)^2) \sum_q e_q^2 f_1(x) D_1(z)} \]

![Graph showing the relationship between $X$ and $Z$.]
Unpolarized DRELL YAN $\cos 2\phi$

\[ \vec{p} + p \rightarrow \mu^- \mu^+ + X \]

\[
\frac{dN}{d\Omega} = \left( \frac{d\sigma}{d^4q} \right)^{-1} \frac{d\sigma}{d^4q d\Omega} = \frac{3}{4\pi \lambda + 3} \left( 1 + \lambda \cos^2 \theta + \mu \sin^2 \theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi \right)
\]  \hspace{1cm} (2)

Angles refer to the lepton pair orientation in their COM frame relative and the initial hadron’s plane. Asymmetry parameters, $\lambda, \mu, \nu$, depend on $s, x, m_{\mu\mu}^2, q_T$


- Leading twist $\cos 2\phi$ azimuthal asymmetry depends on $T$-odd distribution $h_{1}^\perp$.

\[
\nu = \frac{2 \sum_a e_a^2 \mathcal{F} \left[ (2p_{\perp} \cdot k_{\perp} - p_{\perp} \cdot k_{\perp}) \frac{h_{1}^\perp(x,k_T)\bar{h}_{1}^\perp(x,p_T)}{M_1 M_2} \right]}{\sum_{a,\bar{a}} e_{a}^2 \mathcal{F}[f_1 \bar{f}_1]}
\] \hspace{1cm} (3)

Convolution integral

\[ \mathcal{F} \equiv \int d^2p_{\perp} d^2k_{\perp} \delta^2(p_{\perp} + k_{\perp} - q_{\perp}) f^a(x, p_{\perp}) \bar{f}^a(x, k_{\perp}) \]
Higher twist comes in

\[
\nu = \frac{2 \sum_a e_a^2 \mathcal{F} \left[ (2p_\perp \cdot k_\perp - p_\perp \cdot k_\perp) \frac{h_{1\perp}^+(x, k_T^2)}{M_1 M_2} \right]}{\sum_{a, \bar{a}} e_a^2 \mathcal{F}[f_1 \bar{f}_1]} + \nu_4 \left[w_4 f_1 \bar{f}_1\right]
\]

\[
\nu_4 = \frac{\frac{1}{Q^2} \sum_a e_a^2 \mathcal{F} \left[ w_4 f_1(x, k_\perp) \bar{f}_1(x, p_\perp) \right]}{\sum_a e_a^2 \mathcal{F} \left(f_1(x, k_\perp) \bar{f}_1(x, p_\perp)\right)},
\]

where the weight

\[
w_4 = 2 \left( \hat{n} \cdot (k_\perp - p_\perp) \right)^2 - (k_\perp - p_\perp)^2
\]
Gamberg Goldstein,... In prep $s = 50 GeV^2$, $x = 0.2 - 1.0$, and $q = 3.0 - 6.0 GeV$ and $q_T = 0 - 3.0 GeV$ : DATA from E615 Conway et al. PRD:1989

JPS-DNP Maui, 18-22 Sept. 2005
SIDIS: Jaffe and Ji PRL:1993 encountered at twist three level Estimate of this effect, Gamberg, Hwang, Oganessyan PLB:2004

\[ A_{LT} = \frac{\lambda_e |S_T| \sqrt{1 - y} \frac{4}{Q} \left[ M x g_T(x) D_1(z) + M_t h_1(x) \frac{E(z)}{z} \right]}{\left[1 + (1 - y)^2\right] \frac{1}{y} f_1(x) D_1(z)} \]

\( A_{LT} \) for \( \pi^+ \) production function of \( x \) and \( z \) at 27.5 GeV energy. The dashed and dot-dashed curves correspond contributions of two terms above respectively, and full curve is sum. Thin curve corresponds to 6 GeV and the thick to 12 GeV energies.
Bean Asymmetry  Estimate of this effect, Gamberg, Hwang, Oganessyan PLB:2004

$$\langle |P_{h\perp}| \sin \phi \rangle_{LU} = \lambda_e \sqrt{1 - y} \frac{4}{Q} M M_h \left[ x e(x) z H_1^{(1)}(z) + h_1^{(1)}(x) E(z) \right],$$

$A_{LU}$ for $\pi^+$ production as a function of $x$ and $z$ at 27.5 GeV energy. Dashed and dot-dashed curves correspond first and second terms above respectively, and full curve, the sum.

JPS-DNP Maui, 18-22 Sept. 2005
JLAB Kin. 6 and 12 GeV
SUMMARY

- Going beyond the collinear approximation in PQCD recent progress has been achieved in characterizing transverse SSA and azimuthal asymmetries in terms of absorptive scattering.

- Central to this understanding is the role that transversity properties of quarks and hadrons assume in terms of correlations between transverse momentum and transverse spin in QCD hard scattering.

- These asymmetries provide a window to explore novel quark distribution and fragmentation functions which constitute essential information about the spin, transversity and generalized momentum structure of hadrons.

- Along with the chiral odd transversity $T$-even distribution function, existence of $T$-odd distribution and fragmentation functions can provide an explanation for the substantial asymmetries that have been observed in inclusive and semi-inclusive scattering reactions.

- We consider the angular correlations in semi-inclusive DIS and Drell Yan from the standpoint of “rescattering” mechanism which generate $T$-odd, intrinsic transverse momentum, $k_{\perp}$, dependent distribution and fragmentation functions at leading twist.

- We have evaluated $T$-odd contributions to azimuthal and SSA and modeled intrinsic $k_{\perp}$ with Gaussian “regularization” in $\langle k_{\perp} \rangle$.

- Azimuthal asymmetries in Drell Yan and SSA measured at HERMES and COMPASS, JLAB, Belle, GSI-PAX may reveal the extent to which these leading twist $T$-odd effects are generating the data.