Transversity and Meson Photoproduction

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ABSTRACT

Both meson photoproduction and semi-inclusive deep inelastic scattering can potentially probe transversity in the nucleon. We explore how that potential can be realized dynamically. The role of rescattering in exclusive and inclusive meson photoproduction as a source for transverse polarization asymmetry is reexamined. We use a dynamical model to calculate the asymmetry and relate that to the transversity distribution of the nucleon.

Introductory remarks

- Tensor charge of the nucleon - the first moment of the transversity distribution $h_1(x)$.
- Theoretically it is as fundamental to our understanding of the spin structure of the nucleon as is the axial charge (the first moment of the helicity distribution).
- Can not be measured in deep inelastic scattering.
- Will contribute to the Drell-Yan process and some semi-inclusive asymmetries.
- Transversity in helicity basis:
- $|\perp/\top>\sim(|+>\pm|->)$
- Or in terms of Pauli-Lubanski tensor:
- Simplicity in spin-dependent nucleon-nucleon scattering (Goldstein and Moravcsik)
- $f_{a,b;c,d}(s,t)$ for transversity (a and b $\rightarrow$ c and d)
- Transversity distribution in the nucleon:
  - $$\int_0^1 \left(\delta q^a(x) - \delta\overline{q}^a(x)\right) dx = \delta q^a$$
    (for flavor index a)
  - Leading twist transversity distribution function, $\delta q^a(x)$, or $h_1(x)$, or ... (helicity counterpart $\Delta q^a(x)$).

- Skewed distributions - functions of x_{Bj} **and** k_T In integrating over k_T get usual functions of x_{Bj}.

  - In Deeply Virtual Compton Scattering (DVCS) in the context of skewed parton distributions (Radyushkin, Ji).
  - Distributions which can flip quark helicity – k_T counterparts of the usual quark transversity distributions e.g. Forward limit $H_T^a(x,\xi,t) \longrightarrow$ ordinary tranversity distribution, $H_T^a(x,0,0) = \delta q^a(x)$.
  - First moment is $t \longrightarrow 0$ limit of form factor associated with helicty flip amplitude $A_{++,--}$ *survives* in forward limit (Diehl).
  - Signals orbital angular momentum.

Spin-flavor symmetry

Gamberg & Goldstein, PRL87,242001(2001)

- Flavor components of nucleon tensor charge defined from the local operator nucleon matrix element of the tensor current,
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$$\langle P, S_T|\overline{\psi}\sigma^{\mu\nu}\gamma_5\frac{\lambda^a}{2}\psi|P, S_T\rangle = 2\delta q^a(\mu^2)(P^\mu S_T^\nu - P^\nu S_T^\mu). \tag{1}$$
- Model: nucleon matrix element of the tensor current is dominated by the lowest lying axial vector mesons.
- $$\begin{aligned}&\langle P, S_T|\overline{\psi}\sigma^{\mu\nu}\gamma_5\tfrac{\lambda^a}{2}\psi|P, S_T\rangle \\ &= \lim_{k^2\to 0}\sum_{\mathcal{M}} \frac{\langle 0|\overline{\psi}\sigma^{\mu\nu}\gamma_5\frac{\lambda^a}{2}\psi|\mathcal{M}\rangle\langle \mathcal{M},P,S_T|P,S_T\rangle}{M_{\mathcal{M}}^2-k^2} \quad .\end{aligned}$$
- Summation is over mesons with $J^{PC} = 1^{+-}$ that couple to nucleon via tensor current; namely charge conjugation odd axial vector mesons – isoscalars $h_1(1170)$, $h_1(1380)$ and the isovector $b_1(1235)$. Vertex functions for nucleon coupling to h_1 and b_1 meson
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$$\langle MP|P\rangle = \frac{ig_{\mathcal{M}NN}}{2M_N}\overline{u}\left(P,S_T\right)\sigma^{\mu\nu}\gamma_5 u\left(P,S_T\right)\varepsilon_\mu k_\nu, \tag{2}$$

- Corresponding matrix elements of meson decay amplitudes

$$\langle 0|\overline{\psi}\sigma^{\mu\nu}\gamma_5\frac{\lambda^a}{2}\psi|\mathcal{M}\rangle = i f^a_{\mathcal{M}}\left(\varepsilon_\mu k_\nu - \varepsilon_\nu k_\mu\right). \qquad (3)$$

  P_μ is nucleon momentum, k_μ and ε_ν are meson momentum and polarization. $g_{\mathcal{M}NN}$ and $f_{\mathcal{M}}$ are coupling and decay constants.

- Phenomenological mass symmetry among lowest lying axial vector mesons that couple to tensor charge, spin-flavor symmetry $SU(6)_W \otimes O(3)$ multiplet structure (sakita). 1^{+-} h_1 and b_1 mesons in $(35 \otimes L = 1)$ multiplet that contains $J^{PC} = 1^{+-}, 0^{++}, 1^{++}, 2^{++}$. These mesons couple "symmetrically" to baryons

- $$\mathrm{Tr}(J\cdot\Phi) = g\left(\quad \ldots + c_1\frac{J^{5\,a}_{\mu\nu}F^{\mu\nu}_a}{4M_N} + c_2 J^{5\,a}_\mu A^\mu_a + \quad \ldots\right),$$

  where J and Φ are nucleon "super" current and meson "super" multiplet.

- Reducing to 2-component form:
- $\mathcal{L}^{(SU(6)\times O(3))}_{\mathcal{M}NN} =$
  $g\ N^\dagger\left(\quad \ldots + \frac{5}{3}\sigma\cdot\hat{k}\hat{P}\cdot\varepsilon_{b_1} + \frac{i}{\sqrt{2}}\left(\hat{P}\times\hat{k}\right)\cdot\varepsilon_{a_1} + \quad \ldots\right) N$
- Identify $SU(6)_W \times O(3)$ Yukawa couplings.
- Meson decay constants determined from $SU(6)_W \otimes O(3)$ *quark current* couplings to the mesons.

- $\mathcal{L}_{\mathcal{M}qq}^{(SU(6)\times O(3))} =$
  $f\ \chi^\dagger \Big(\quad .. + \sigma \cdot \hat{k}\hat{P} \cdot \varepsilon_{b_1} + \frac{i}{\sqrt{2}} \left(\hat{P} \times \hat{k} \right) \cdot \varepsilon_{a_1} + \quad .. \Big)\, \chi \qquad .$
- Relate a_1 decay constant measured in τ decay (Tsai) $f_{a_1} = (0.19 \pm 0.03)\mathrm{GeV}^2$, and the a_1NN coupling constant $g_{a_1NN} = 7.49 \pm 1.0$ (Birkel & Fritzsch) to meson decay constants and coupling constants. Find
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$$f_{b_1} = \frac{\sqrt{2}}{M_{b_1}} f_{a_1}, \quad g_{b_1NN} = \frac{5}{3\sqrt{2}} g_{a_1NN}. \tag{4}$$
- 5/3 from $SU(6)$ factor $(1 + F/D)$. $\sqrt{2}$ arises from $L = 1$ relation between the 1^{++} and 1^{+-} states. Resulting value of $f_{b_1} \approx 0.21 \pm 0.03$ agrees well with sum rule determination of 0.18 ± 0.03 (Belyaev & Oganesian).
- h_1 couplings related to b_1 couplings via $SU(3)$ & $SU(6)$ F/D value,
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$$f_{b_1} = \sqrt{3} f_{h_1}, \quad g_{b_1NN} = \frac{5}{\sqrt{3}} g_{h_1NN} \tag{5}$$
- For transverse polarized Dirac particles, $S^\mu = (0, S_T)$ these values, yield isovector & isoscalar parts of tensor charge,

- $$\delta q^v = \frac{f_{b_1} g_{b_1 NN} \langle k_\perp^2 \rangle}{\sqrt{2} M_N M_{b_1}^2}\,, \quad \delta q^s = \frac{f_{h_1} g_{h_1 NN} \langle k_\perp^2 \rangle}{\sqrt{2} M_N M_{h_1}^2}, \qquad (6)$$

- Transverse momentum – tensor couplings involve helicity flips carrying kinematic factors of $\vec{k}_T$ from rotational invariance. Squared 4-momentum transfer of external hadrons $\longrightarrow 0$ but quark fields carry intrinsic $k_\perp$ (determined from Drell-Yan & heavy vector boson production). $\langle k_\perp^2 \rangle$ range $(0.58 \text{ to } 1.0\ \mathrm{GeV}^2)$. (R.K. Ellis, *et al.)*

Mixing & results

- Isoscalar 1^{+-} not pure octet $h_1(8)$. Experimentally, higher mass $h_1(1380)$ in $K + \bar{K} + \pi's$ decay channel (Abele *et al.* , 97, etc.) but $h_1(1170)$ detected in multi-pion channel (Ando *et al.* , 92). Decay pattern indicates higher mass state is strangeonium & decouples from lighter quarks – well known mixing of vector meson nonet. h_1 states are mixed $h_1(8)$ & $h_1(1)$

- $$f_{h_1(1170)} = f_{b_1}\,, \quad g_{h_1(1170)NN} = \frac{3}{5} g_{b_1 NN}, \qquad (7)$$

with the $h_1(1380)$ not coupling nucleon. These symmetry relations yield

- $$\delta u(\mu^2) = (0.58 \text{ to } 1.01) \pm 0.20, \quad \delta d(\mu^2) = -(0.11 \text{ to } 0.20) \pm$$

- Similar to other model calculations, e.g. lattice (Aoki, *et al.*); QCD sum rules (He & Ji; Jin & Tang; Belyaev & Oganesian); light cone quark (Ma, Schmidt, Soffer); bag model (Jaffe & Ji); quark soliton (Gamberg, Reinhardt, Weigel; etc.). Scale $\mu \approx 1$ GeV, set by N mass and/or $< m_{Axial} >$. Evolution to higher scales determined by anomalous dimensions of tensor charge (Artru & Mekhfi) but slowly varying.
- Symmetry relations that connect b_1 couplings to a_1 couplings can be used to relate directly isovector tensor charge to axial vector coupling g_A via a_1 dominance for isovector longitudinal charges (Birkel & Fritzsch),

- $$\Delta u - \Delta d = \frac{g_A}{g_V} = \frac{\sqrt{2} f_{a_1} g_{a_1 NN}}{M_{a_1}^2}. \tag{9}$$

- Hence for δq^v we have

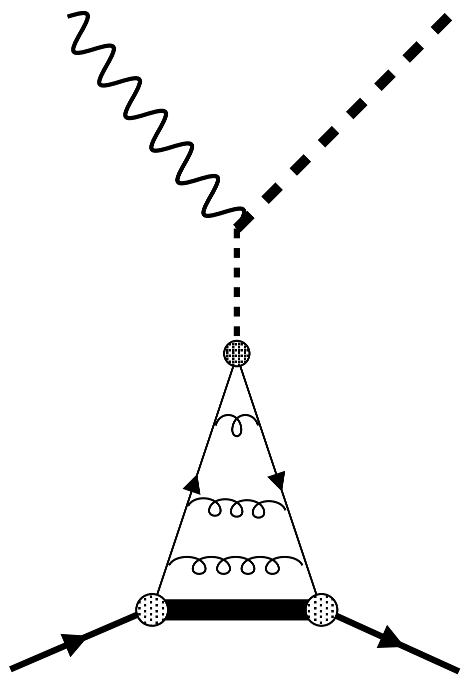
$$\delta u - \delta d = \frac{5}{6} \frac{g_A}{g_V} \frac{M_{a_1}^2}{M_{b_1}^2} \frac{\langle k_\perp^2 \rangle}{M_N M_{b_1}}, \tag{10}$$

- Relation between h_1 & b_1 couplings in same $SU(3)$ multiplet leads to a more direct result
-

$$\delta u + \delta d = \frac{3}{5}\frac{M_{b_1}^2}{M_{h_1}^2}\delta q^v \,, \tag{11}$$

Relation to photoproduction

- Appearance of factor $\langle k_T^2 \rangle$ in δq arises from kinematic structure of exchange picture as indicated in Fig.1.



- Consider meson photoproduction in exchange model, for large energies and relatively small momentum transfer Δ. For transverse photons have 4 independent helicity or transversity amplitudes.

- $$f_1 = f_{1+,0+} \propto \Delta^1,\ f_2 = f_{1+,0-} \propto \Delta^0, \tag{12}$$
$$f_3 = f_{1-,0+} \propto \Delta^2,\ f_4 = f_{1-,0-} \propto \Delta^1. \tag{13}$$

- The minimum kinematically allowed power is indicated. In single hadron exchange (or Regge pole exchange) parity conservation requires

- $$f_1 = \pm f_4 \text{ and } f_2 = \mp f_3 \tag{14}$$
for even/odd parity exchanges (for s $\gg$ $|t|$). These pair relations, along with a single hadron exchange model, force f_2 to behave like f_3 for small Δ. This introduces the k_T^2 factor into the f_2 amplitude that determines the transversity transfer. The polarized target asymmetry is given by

- $$P_y = \frac{2Im(f_1^* f_3 - f_4^* f_2)}{\sum_{j=1...4} |f_j|^2} \tag{15}$$
$$= -\frac{Im(f_1^{+*} f_2^+ + f_1^{-*} f_2^-)}{\sum_{j=1...4} |f_j|^2} \tag{16}$$

- Non-zero single spin asymmetry requires interference between single helicity flip and non-flip and/or double flip amplitudes.

Asymmetry arises from rescattering corrections (or Regge cuts or eikonalization or loop corrections) to single hadron exchanges. One of the amps in the product must acquire a different phase – relative imaginary part.

- Rescattering – loop integration – integrates over internal $\vec{k}_T$. Allows $f_2 \propto \Delta^0$ & effectively introduces $\langle k_T^2 \rangle$.

- True for inclusive process as well, where only one final hadron is measured – a relative phase in a helicity flip three body amplitude is required. How does this picture connect to the parton distributions?

- Semi-Inclusive Deep Inelastic Scattering (SIDIS) – far off-shell photon photoproduces hadron inclusively.

$$(q + P - k)^2 = M_X^2 = \tag{17}$$

- Brodsky, Hwang and Schmidt (BHS) recently calculated rescattering corrections to SIDIS target nucleon asymmetry. They use scalar diquark spectator model ($M_X = m_{scalar}$) to obtain result. Leading twist effect. Not transparently related to parton distribution function.

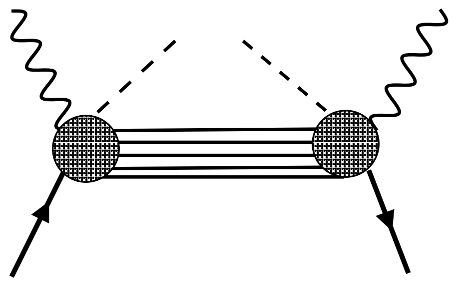


Fig.2 Inclusive Scattering: Photoproduction of Meson

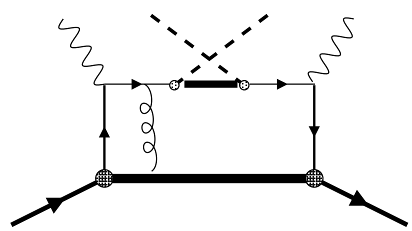
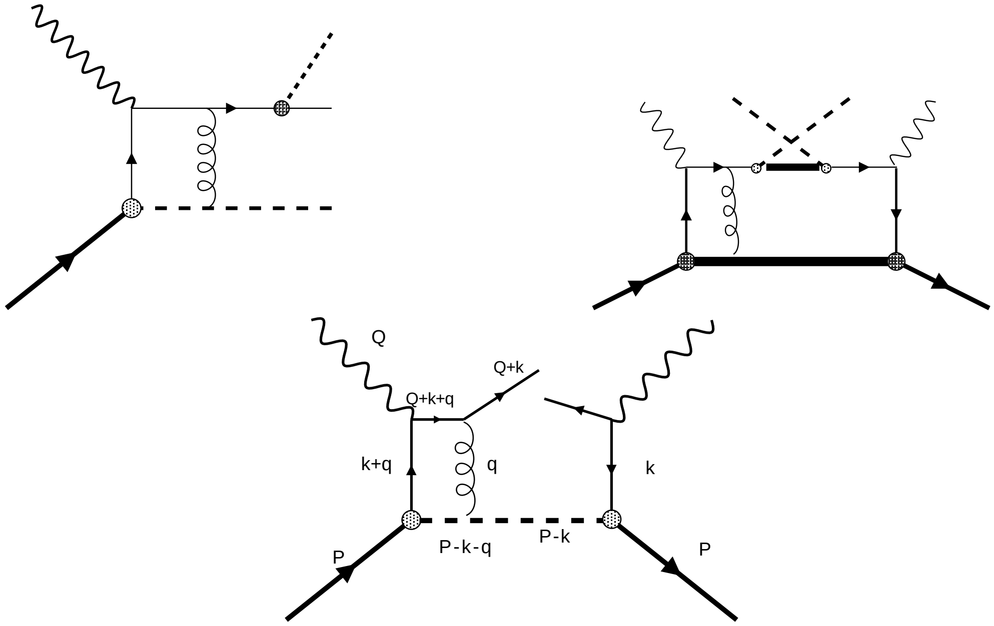


Fig.3 SIDIS without Rescattering

Next: Fig.4 SIDIS amp with Rescattering

Fig.5 Semi-inclusive Deep Inelastic Scattering with Rescattering

Fig.6 SIDIS Spectator Model with Rescattering



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- Collins showed that factorization still holds. BHS is interpreted by Ji & Yuan to give function $f_{1T}^{\perp}$. Direct parton distribution interpretation is alterred, but rescattering comes from lowest order gauge links. Odd T – Sivers function.

- Is this a physical observable amenable to experimental study? BHS:

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$$\mathcal{P}_y \propto \frac{(xM+m)k_x}{[(xM+m)^2+\vec{k}_\perp^2]} \frac{\Lambda(\vec{k}_\perp^2)}{\vec{k}_\perp^2} \ln\left(\frac{\Lambda(\vec{k}_\perp^2)}{\Lambda(0)}\right) \qquad (18)$$

where

$$\Lambda(\vec{k}_\perp^2) = \vec{k}_\perp^2 + x(1-x)\left(-M^2 + \frac{m^2}{x} + \frac{\lambda^2}{1-x}\right) . \quad (19)$$

- BHS calculated rescattering contribution to amp for $\gamma^* + N \rightarrow q + \text{ scalar diquark}$ with the nucleon transversely polarized. Assumed quark fragments into a meson. Meson's role is to set quark's momentum direction (D(z)=1). Asymmetry (would vanish at tree level) involves integrated $f_{1T}^\perp(x)$ (Ji & Yuan).
- Pseudoscalar ($\pi \& \eta$) deep inelastic electroproduction is related to matrix elements of quark field operator tensor current – involving Dirac matrices $\gamma^+\gamma^T\gamma^5$ (Jaffe & Ji).
- For pseudoscalar meson electroproduction (Ji & Yuan)
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$$\begin{aligned} s_T^i \Delta' f(x, k_T) &= \frac{1}{2}\sum_n \int \frac{d\xi^- d^2\xi_\perp}{(2\pi)^3} e^{-i(\xi^- k^+ - \vec{\xi}_\perp \vec{k}_\perp)} \\ &\times \langle P|\overline{\psi}(\xi^-, \xi_\perp)|n\rangle \\ &\times \langle n| \left(-ie_1 \int_0^\infty A^+(\xi^-, 0) d\xi^-\right) \\ &\times \gamma^+\gamma^i\gamma^5\psi(0)|P\rangle + \text{h.c.} , \qquad (20) \end{aligned}$$

where e_1 is the charge of the struck quark and n represents intermediate di-quark states.

- Following Ji and Yuan, using an effective Lagrangian for scalar diquark interactions with quarks, gluons and the nucleon, one loop expression from Fig. 2,
-

$$
\begin{aligned}
s_T^i \Delta' f(x, k_T) &= \frac{-ig^2 e_1 e_2}{4(2\pi)^3 \Lambda(k_\perp^2)} \int \frac{d^4 q}{(2\pi)^4} \overline{U}(PS)(\not{k} + m) \\
&\times \gamma^+ \gamma^i \gamma^5 (\not{k} + \not{q} + m) U(PS) \\
&\times \frac{2(1-x) - q^+}{q^+ + i\epsilon} \frac{1}{(k+q)^2 - m^2 + i\epsilon} \\
&\times \frac{1}{(P-k-q)^2 - \lambda^2 + i\epsilon} \frac{1}{q^2 + i\epsilon} + \text{h.c.}
\end{aligned}
\tag{21}
$$

where q^μ is gluon momentum, M, m. λ are masses of nucleon, quark and diquark.

- Using contour integration on q^-, adding hermitian conjugate, and finally integrating over $\vec{q}_\perp$ doing azimuthal integration first.

$$
\begin{aligned}
s_T^i \Delta f_T(x,k_\perp) = {} & \frac{e_1 e_2 g^2}{2(2\pi)^4} \frac{1-x}{\Lambda(k_\perp^2)} \\
& \Big\{ \Big(S_T^i [(m+xM)^2 + k_\perp^2] + 2k_\perp^i \mathbf{S}_T \cdot \mathbf{k}_\perp \Big) \\
& \qquad \times \frac{1}{k_\perp^2 + \Lambda(0)^2 + \lambda_g^2} \left(\ln \frac{\Lambda(k_\perp^2)}{\Lambda(0)} + \ln \frac{k_\perp^2 + \lambda_g^2}{\lambda_g^2} \right) \\
& \qquad - \Big(S_T^i k_\perp^2 + 2k_\perp^i \mathbf{S}_T \cdot \mathbf{k}_\perp \Big) \frac{1}{k_\perp^2} \ln \frac{\Lambda(k_\perp^2)}{\Lambda(0)} \Big\}
\end{aligned}
$$

- The Abelian gluon mass (chosen at $\lambda_g \approx 1\ GeV$) indicative of χSB scale
- First part has same structure as tree level result (Jakob, Mulders, Rodriques '97). It is a combination of $h_{1T}(x,k_T)$ and $h_{1T}^\perp(x,k_T)$. Integrating over k_T leaves $h_1(x)$. Second part has different structure than tree level - rescattering only. It is proportional to one loop result for $f_{1T}^\perp$ (Ji & Yuan) and $\mathcal{P}_y$ in BHS.
- When combined with a measure of transversely polarized quarks, fragmentation function $H_1^\perp(z)$ (Collins), integrated $h_{1T}(x)$ and $h_{1T}^\perp(x)$ will contribute to weighted meson azimuthal asymmetries (Kotzinian & Mulders, 97; Boer & Mulders, 98). Weighting by powers of k_T gives asymmetries in $\sin(n\phi_{meson})$.

- Tree level spin-independent contribution
- $$f(x, k_\perp) = \frac{g^2}{(2\pi)^3} \frac{(1-x)}{\Lambda^2(k_\perp^2)} \left[\left(m + xM\right)^2 + k_\perp^2 \right]$$

Final State Interactions: Estimation of T-ODD $h_1^\perp(x, \mathbf{k}_\perp)$

- Easy to show: vanishes at tree level as $f_{1T}^\perp$
- Projecting spin independent piece from above
- Governs SSA in π production: transverse spin in unpolarized target
- FSI are infrared finite
- Implications for transversity
- Gamberg & Goldstein (in prep)

$$h_1^\perp(x, \mathbf{k}_\perp) = \frac{e_1 e_2 g^2}{2(2\pi)^4} \frac{(m + xM)(1-x)}{\Lambda(k_\perp^2)} \varepsilon_{(T)}^{\perp j} k_{\perp j} \frac{1}{k_\perp^2} \ln \frac{\Lambda(k_\perp^2)}{\Lambda(0)} \quad (22)$$

- $\varepsilon_{(T)}^{\perp j} = \varepsilon^{+-\perp j}$

Some conclusions

- Spin-flavor symmetry relates tensor charges to axial charges when supplemented with axial vector dominance.
- Axial vector dominance produces $\langle k_T^2 \rangle$ as appears in rescattering models.
- Transversely polarized nucleon asymmetries in exclusive and inclusive meson photoproduction require rescattering for interference. SIDIS likewise. Exchange picture merges with struck quark when rescattering effective.
- Spectator model yields simple relations. Are they too simple?
- To do:
  - specify asymmetry precisely
  - compare k_T dependences from different models
  - consider more realistic intermediate states (that can carry spin information)