Transversity Properties of Quarks and Nucleons in SIDIS and Drell Yan

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- Remarks on Transversity and Spin Structure of Nucleon
- ⋆ Minining Transversity Through Hard Scattering
- Role of Intrinsic k_T in Understanding Transversity
- ⋆ Novel Transversity Properties in Hard Scattering
- ⋆ Reaction Mechanism-Rescattering in T-odd Structure and Fragmentation Functions
- ⋆ Estimates of the Collins and Sivers Asymmetries
- ⋆ Double T-odd $\cos 2\phi$ asymmetry & higher twist
- ⋆ Beam Asymmetry
- ⋆ Drell Yan
- Conclusions

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Introductory Remarks: Transversity

See Review Phys. Rep. 2002, Ratcliffe, Barone, Drago

- Transversity "δq" as combinations of helicity states

$$|\perp/\top> = \frac{1}{\sqrt{2}}(\,|+> \quad \pm \quad |->\,)$$

Goldstein & Moravcsik, Ann. Phys. 1976 introduced reveal underlying simplicity spin-dependent nucleon-nucleon scattering amps $f_{a,b;c,d}(s,t)$

- Connection with spin structure of nucleon revealed through the quark distribution

$$h_1^a(x) = \delta q^a(x) \tag{1}$$

- First moment, tensor charge Jaffe & Ji, PRL:1991

$$\int_0^1 (\delta q^a(x) - \delta \overline{q}^a(x))\, dx = \delta q^a$$

- LO anomalous dimensions Baldracchini *et al* Fortsch. Phys. 1981, Artru & Mekhfi, ZPC:1990

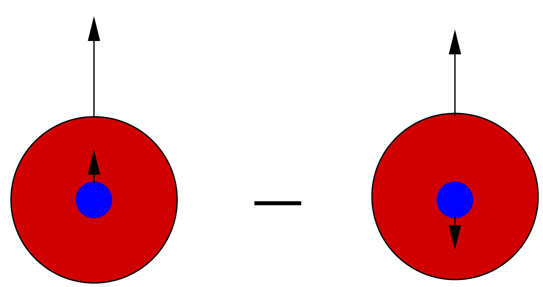
TRANSVERSITY Understood Context Parton Model in IMF

- Instead of diagonalizing free Hamiltonian w/r to HELICITY use $\perp/\top$ TRANSVERSITY eigenstates: $Q_{\top/\perp} = \frac{1}{2}\left(\mathbf{1} \mp \gamma_5 \not{S}_\perp\right)$
  - ⋆ Projector $Q_{\top/\perp}$ commutes with free-quark Hamiltonian and $P_\pm \psi = \psi_\pm$, is a *good* light cone operator

While $g_1(x)$ is obscure $g_1(x) = \mathrm{Re}\frac{2}{x}\langle P\hat{\mathbf{e}}_3 | b^\dagger_\perp(xP) b_\top(xP) | P\hat{\mathbf{e}}_3\rangle$
in transversity basis

$$h_1(x) \;=\; \frac{1}{x}\langle P\hat{\mathbf{e}}_\perp | b^\dagger_\perp(xP) b_\perp(xP) - b^\dagger_\top(xP) b_\top(xP) | P\hat{\mathbf{e}}_\perp\rangle$$

$h_1(x)$ **is probability to find quark with spin polarized along transverse spin direction minus oppositely polarized case**



$h_1(x)$

Theoretically among other things

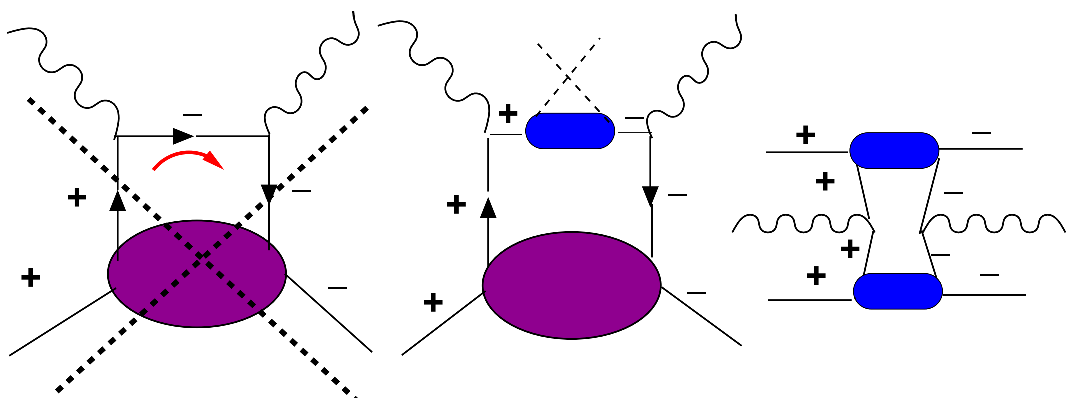
⋆ Soffer's inequality (Soffer, PRL:1995) & possible saturation/violation (Goldstein Jaffe Ji, PRD:1995) places bounds on leading twist distributions
$\left|2\delta q^a(x,Q^2)\right| \leq q^a(x,Q^2) + \Delta q^a(x,Q^2)$

⋆ NLO analysis Martin & Vogelsang *et al*, PRD: 1998; indicates bound respected under evolution

• Decouples leading twist DIS:
Helicity of struck quark must flip to probe transversity chiral-odd

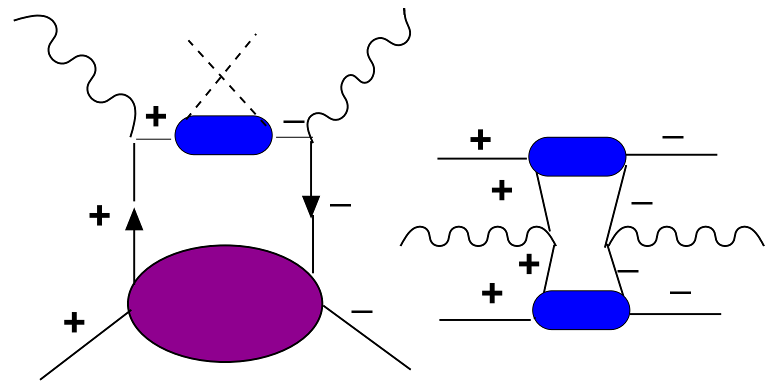
⇒require chiral-odd partner
⇒ and one or more hadrons

Hard scattering conserves chirality
thus hadron helicity flip suppressed in DIS by m/Q



Mining Transversity thru Hard Scattering

Drell-Yan $p_\perp\, p_\perp \Rightarrow l^+ l^-\ X$ (2 in the initial state)
SIDIS $l\ p_\perp \Rightarrow l'\, h\ X$ (1 in the initial 1 in the final)



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

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

⋆ SIDIS: Jaffe and Ji PRL:1993 encountered at twist three level

Estimate, Gamberg, Hwang, Oganessyan PLB:2004

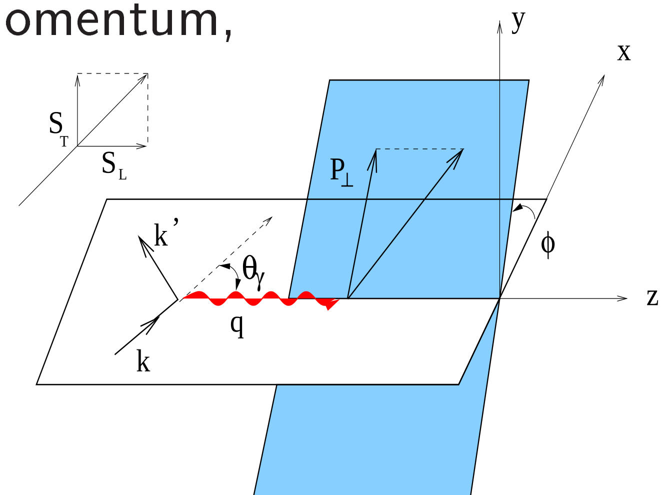
$$A_{LT} = \frac{\lambda_e|\boldsymbol{S}_T|\sqrt{1-y}\,\frac{4}{Q}\left[M\,x\,g_T(x)D_1(z)+M_h\,h_1(x)\frac{E(z)}{z}\right]}{\frac{[1+(1-y)^2]}{y}\,f_1(x)D_1(z)}$$

SIDIS and Transversity at Leading Twist $k_\perp$ Dependence

- Collins NPB:1993, Kotzinian NPB:1995, Mulders, Tangermann PLB:1995

  Transversity thru SSA in the fragmenting hadron's momentum,

  ϕ, angle between $[k\ q]$ and $[P_h\ q]$ ϕ_S, angle of the target spin vector

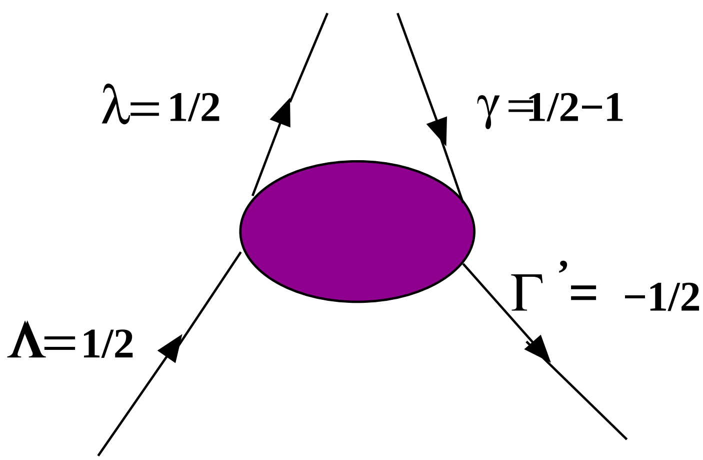


$$\langle \frac{P_{h\perp}}{M_\pi} \sin(\phi+\phi_s) \rangle_{UT} \propto h_1(x) z H_1^{\perp(1)}(z)$$

Beyond Colinearity

Hadron helicity flip due to quark orbital ang. momentum. Quarks have intrinsic transverse momentum. Helicity flip occurs from cons of J.

Cross section differential in transverse momentum. SSA not surpressed by inverse powers of the hard scale. Quarks in target, and fragmentation region possess intrinsic transverse momentum $p_\perp$, $k_\perp$

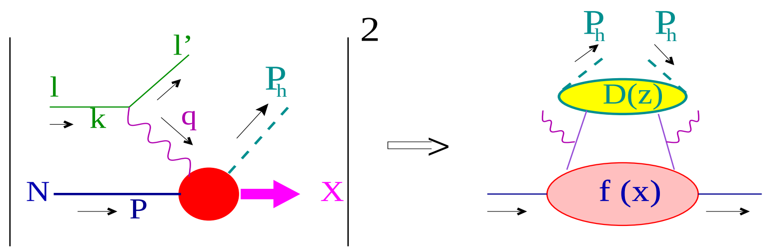


Origins/Mechanism: AAs and SSAs

• In parton model SSA and azimuthal asymmetries are zero leading order α_s • However, intrinsic k_T dependence & higher order in α_s PQCD generate azimuthal asymmetries

⋆ Georgi, Politzer, PRL:1978: pQCD first order α_s , $\langle \cos\phi \rangle$

⋆ Cahn, PLB: 1978; PRD: 1989; Chay *et al.* PRD: 1991, Oganessyan *et al.*, ZPC: 1998 $\langle \cos 2\phi \rangle$



• Need helicity flip to access transversity through SSA in PQCD

Kane *et al* PRL:1978 Goldstein, Dharmarathna *et al* PR:1991 consists of

$\mathrm{Im}(\mathrm{A_F} \star \mathrm{A_{NF}})$, however goes like $\alpha_s \frac{m_q}{\sqrt{s}}$

• Brodsky, Hwang, and Schmidt PLB: 2002 FSI of gluon produces necessary phase leading to nonzero SSAs at *Leading Twist*: $k_\perp$ & pQCD expansion in α_s

AAs & SSAs Understood via Color Gauge Invariance
$\Longrightarrow$ Novel Transversity Properties of Quarks and Nucleons

Employ Factorized Description

Levelt & Mulders, Mulders & Tangerman, NPB: 1994, 1996, See new work of Ji, Ma, Yuan: 2004, Collins, Metz: 2004

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

Hadronic Tensor

$$\begin{aligned}\mathcal{W}^{\mu\nu}(q,P,P_h) \quad &= \quad \int d^2\boldsymbol{p}_T d^2\boldsymbol{k}_T \delta^2(\boldsymbol{p}_T + \boldsymbol{q}_T - \boldsymbol{k}_T) \\ &\mathrm{Tr}[\Phi(x_B,\boldsymbol{p}_T)\gamma^\mu\Delta(z_h,\boldsymbol{k}_T)\gamma^\nu] + (q \leftrightarrow -q\ ,\ \mu \leftrightarrow \nu)\ ,\end{aligned}$$

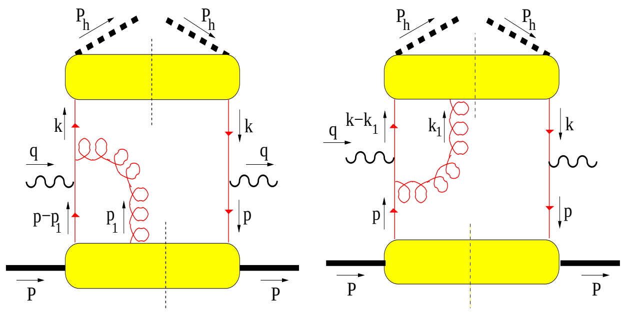
where

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

$$\Delta(k,P_h) = \int \frac{d^3\xi}{4z(2\pi)^3}\ e^{ik\cdot\xi}\ \langle 0\ |\mathcal{G}_{[\xi^+,-\infty]}\psi(\xi)|X;P_h\rangle\langle X;P_h|\overline{\psi}(0)\mathcal{G}^\dagger_{[0,-\infty]}|0\rangle|_{\xi^-=0}$$

- Gauge Invariant Distribution and Fragmentation Functions

  Ji, Yuan & Belitsky PLB: 2002, NPB 2003, Boer, Mulder, Pijlman NPB 2003 more to come ....



- **T-odd Distribution Functions: Transversity Properties of quarks in Hadrons**

  Boer, Mulder, PRD 1998

$$\Delta(z, \boldsymbol{k}_T) = \frac{1}{4}\{D_1(z, z\boldsymbol{k}_T)\, \not{n}_- + H_1^\perp(z, z\boldsymbol{k}_T)\frac{\sigma^{\alpha\beta}k_{T\alpha}n_{-\beta}}{M_h} + \cdots\}.$$

$$\Phi(x, \boldsymbol{p}_T) = \frac{1}{2}\{f_1(x, \boldsymbol{p}_T)\, \not{n}_+ + h_1^\perp(x, \boldsymbol{p}_T)\frac{\sigma^{\alpha\beta}p_{T\alpha}n_{+\beta}}{M} + f_{1T}^\perp(x, \boldsymbol{p}_T)\frac{\epsilon^{\mu\nu\rho\sigma}\gamma^\mu n_+^\nu p_T^\rho S_T^\sigma}{M} + \cdots\},$$

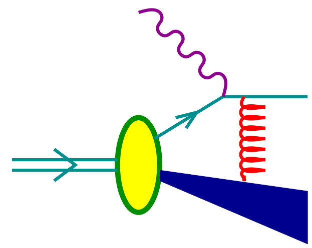
T-Odd Contributions to Asymmetries

- $T-$odd quark distribution functions, *e.g.* $f_{1T}^{\perp}(x,k_\perp)$, $h_1^{\perp}(x,k_\perp)$, (Sivers PRD: 1990, Anselmino & Murgia PLB: 1995 ...) may exist as leading or higher twist effects due to initial/final state interactions or ...

- PRD: 1998 Boer and Mulders considered asymmetries, due to the presence of leading twist T-odd distribution functions, $f_{1T}^{\perp}$, $h_1^{\perp}$

$$
\begin{aligned}
d\sigma_{\lambda,S} \quad &\propto \quad f_1 \otimes D_1 + \frac{k_T}{Q} f_1 \otimes D_1 \cdot \cos\phi + \left[\frac{k_T^2}{Q^2} f_1 \otimes D_1 + h_1^{\perp} \otimes H_1^{\perp} \right] \cdot \cos 2\phi \\
&+ \quad |S_T| \cdot h_1 \otimes H_1^{\perp} \cdot \sin(\phi + \phi_S) + |S_T| \cdot f_{1T}^{\perp} \otimes D_1 \cdot \sin(\phi - \phi_S) \\
&+ \quad \cdots
\end{aligned}
$$

Rescattering-Mechanism: T-Odd Contributions to Asymmetries



- Ji, Yuan & Belitsky PLB: 2002, NPB 2003 describe effect in terms of gauge invariant distribution functions (Collins,Soper NPB: 1982)

$$\Rightarrow \quad \langle P|\overline{\psi}(\xi^-,\xi_\perp)\mathcal{G}^\dagger_{[\xi,\infty]}|X\rangle\langle X|\mathcal{G}_{[0,\infty]}\psi(0)|P\rangle|_{\xi^+=0}$$

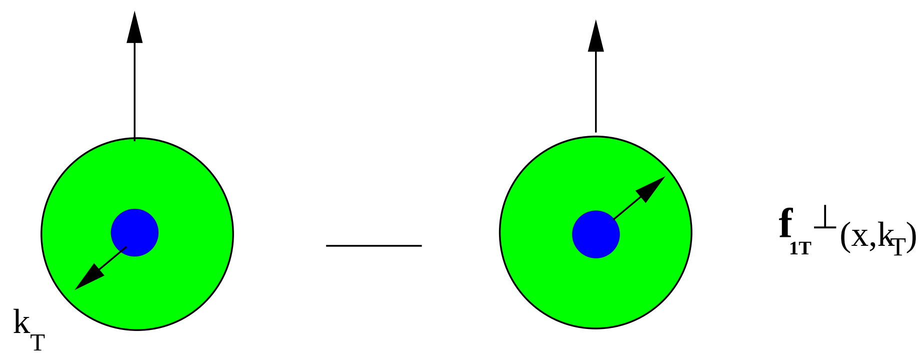
$$\mathcal{G}_{[\xi,\infty]}=\mathcal{G}_{[\xi_T,\infty]}\mathcal{G}_{[\xi^-,\infty]}, \quad \text{where} \quad \mathcal{G}_{[\xi^-,\infty]}=\mathcal{P}exp(-ig\int_{\xi^-}^{\infty}d\xi^- A^+)$$

- 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
$f_{1T}^{\perp}(x,k_\perp)|_{\text{SDIS}} = -f_{1T}^{\perp}(x,k_\perp)|_{\text{DY}}$

Sivers Asymmetry in SIDIS

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



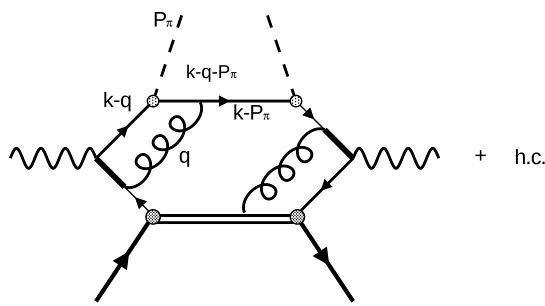
$$\langle \frac{|P_{h\perp}|}{M} \sin(\phi - \phi_S) \rangle_{UT} \quad = \quad |\boldsymbol{S}_T| \frac{(1 + (1-y)^2) \sum_q e_q^2 f_{1T}^{\perp(1)}(x) z D_1^q(z)}{(1 + (1-y)^2) \sum_q e_q^2 f_1(x) D_1(z)},$$

⋆ See HERMES Data, D. Hasch, G. Schnell SPIN04; COMPASS P. Pagano SPIN04, see also STAR DATA

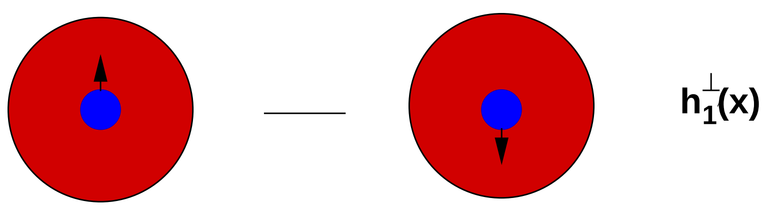
Rescattering to Generate T-Odd Function $h_1^\perp$ In SIDIS

G.G.–ICHEP-proc., Amsterdam: 2002, hep-ph/0209085, PRD, 2003

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



- $h_1^\perp(x, k_\perp)$, represents, number density transversely polarized quarks in an unpolarized nucleons nucleons-complementary to $f_{1T}^\perp(x, k_\perp)$,



Double T-odd $\cos 2\phi$ Asymmetry

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

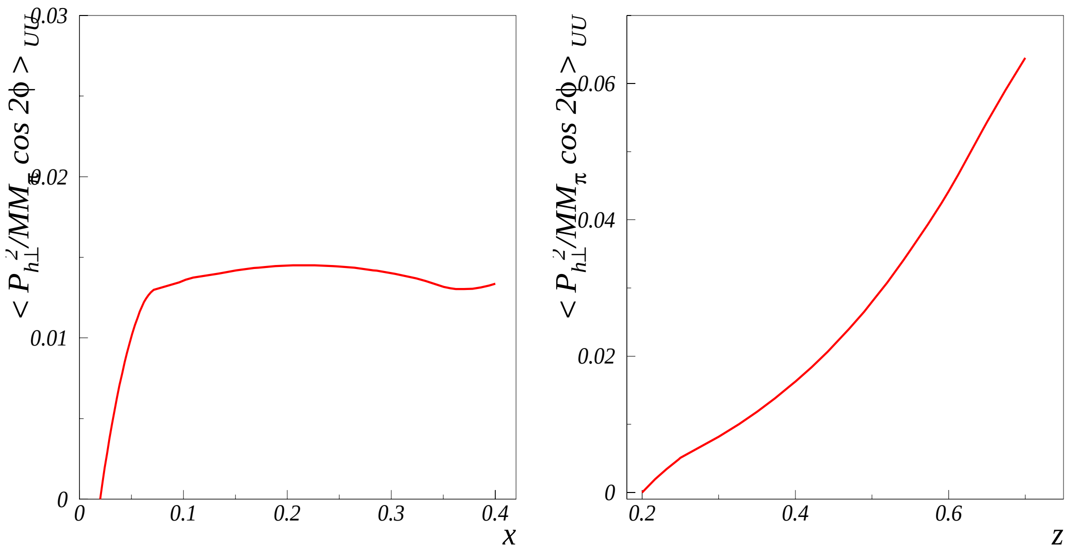
Gamberg, Goldstein, Oganessyan PRD 2003

For the HERMES kinematics

$1\ \text{GeV}^2 \le Q^2 \le 15\ \text{GeV}^2$, $4.5\ \text{GeV} \le E_\pi \le 13.5\ \text{GeV}$,

$0.2 \le z \le 0.7$, $0.2 \le y \le 0.8$, $< P_{h\perp}^2 >= 0.25\ \text{GeV}^2$ and $< P_{h\perp} >= 0.4\ \text{GeV}$

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



Estimates of T-odd Contributions to Azimuthal Asymmetries

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

Brodsky, Hwang, Schmidt, PLB: 2002;

Goldstein, L. Gamberg, ICHEP 2002;

$$h_1^{\perp}(x, k_{\perp}) \quad = \quad \frac{g^2 e_1 e_2}{(2\pi)^4} \frac{(1-x)(m+xM)}{4\Lambda(k_{\perp}^2)} \frac{M}{k_{\perp}^2} \ln \frac{\Lambda(k_{\perp}^2)}{\Lambda(0)}$$

$$\Lambda(k_{\perp}^2) = k_{\perp}^2 + x(1-x)\left(-M^2 + \tfrac{m^2}{x} + \tfrac{\lambda^2}{1-x}\right)$$

- Asymmetry involves weighted function

$$h_1^{(1)\perp}(x) \equiv \int d^2k_{\perp} \frac{k_{\perp}^2}{2M^2} h_1^{\perp}(x, k_{\perp}^2) \quad \textit{diverges}$$

Gaussian Distribution in $k_\perp$

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

Gamberg, Goldstein, Oganessyan, PRD 67 (2003)

$$\langle n|\psi(0)|P\rangle = \left(\frac{i}{\not{k} - m}\right)\frac{b}{\pi}e^{-bk_\perp^2}U(P,S), \quad b \equiv \frac{1}{\langle k_\perp^2\rangle}$$

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

$$h_1^\perp(x,k_\perp) \quad = \quad \frac{e_1 e_2 g^2}{2(2\pi)^4}\frac{b^2}{\pi^2}\frac{(m+xM)(1-x)}{\Lambda(k_\perp^2)}\frac{1}{k_\perp^2}e^{-b\left(k_\perp^2-\Lambda(0)\right)}\left[\Gamma(0,b\Lambda(0))-\Gamma(0,b\Lambda(k_\perp^2))\right]$$

$\Gamma(0,z) \equiv$ incomplete gamma function:

- Check approach: $\lim < k_\perp^2 > \to \infty$ Gaussian width goes to infinity, regain *log divergent* result

Rescattering Mechanism for T-Odd Collins Function

Gamberg,Goldstein,Oganessyan hep-ph/0307139, PRD68,2003, Bacchetta, Metz, Yang hep-ph/0307282, PLB 2004

- Gauge-link contribution to the Collins Function:

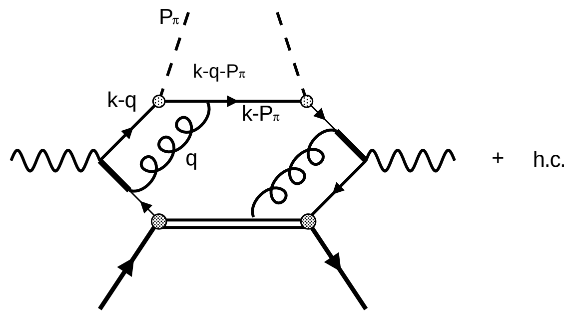


Figure depicts $h_1^\perp \star H_1^\perp \cos 2\phi$ asymmetry.

We evaluate the projection $\Delta^{[i\sigma^{\perp -}\gamma_5]}$, which results in the leading twist, contribution to T-odd pion fragmentation

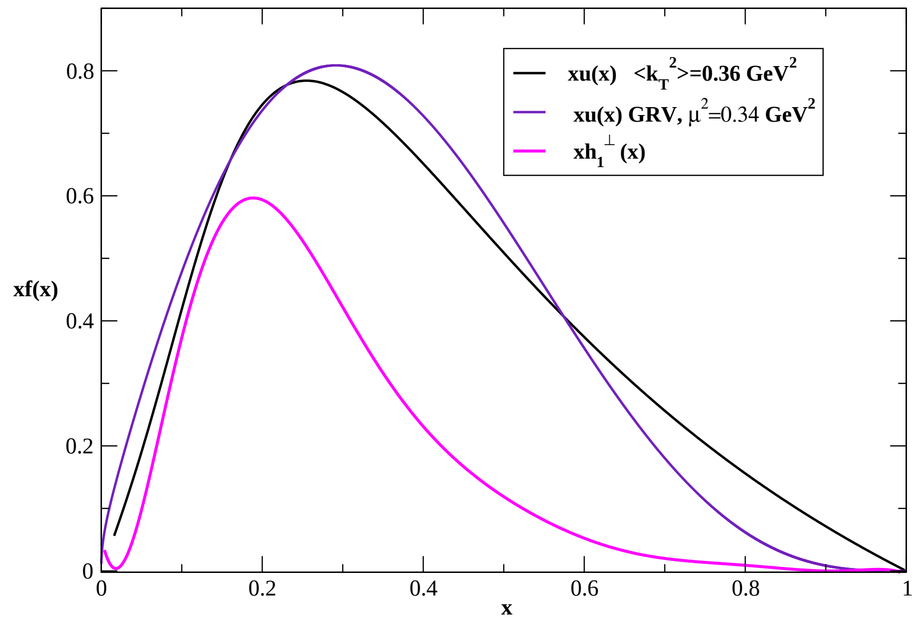
$$H_1^\perp(z,k_\perp) = \frac{N'^2 f^2 g^2}{(2\pi)^4}\frac{1}{4z}\frac{(1-z)}{z}\frac{m}{\Lambda'(k_\perp^2)}\frac{M_\pi}{k_\perp^2}e^{-b'\left(k_\perp^2-\Lambda'(0)\right)}\left[\Gamma(0,b\Lambda'(0))-\Gamma(0,b'\Lambda'(k_\perp^2))\right],$$

where, $\Lambda'(k_\perp^2) = k_\perp^2 + \frac{1-z}{z^2}M_\pi^2 + \frac{\mu^2}{z} - \frac{1-z}{z}m^2$

Unpolarized Structure Function

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

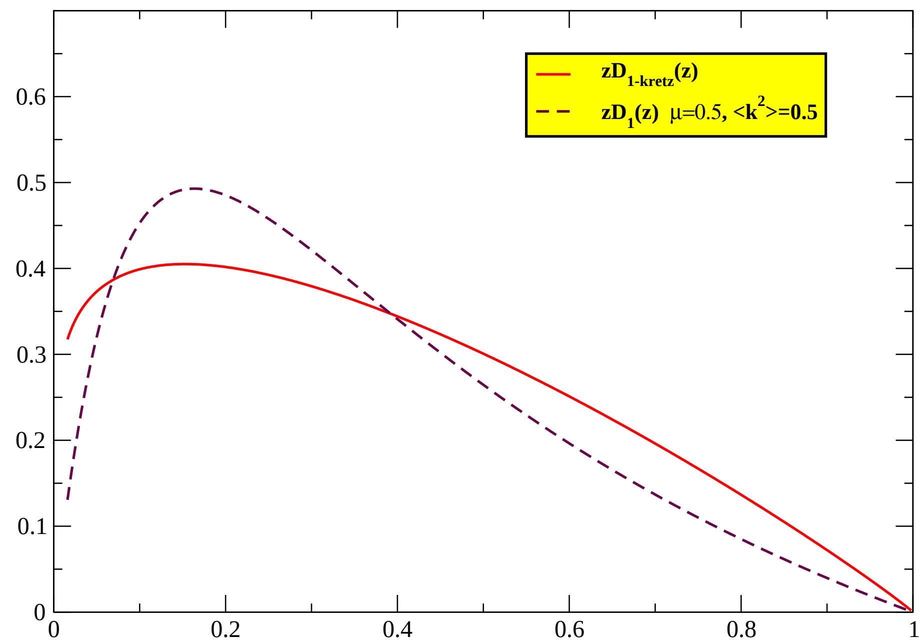
- ⋆ Normalization, $\int_0^1 u(x) = 2$
- Black curve- $xu(x)$
- Purple curve - $xu(x)$ from GRV
- Pink curve $xh_1^{\perp(u)}$



Pion Fragmentation Function

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

which, multiplied by z at $< k_\perp^2 >= (0.5)^2$ GeV^2 and $\mu = m$, estimates the distribution of Kretzer, PRD: 2000

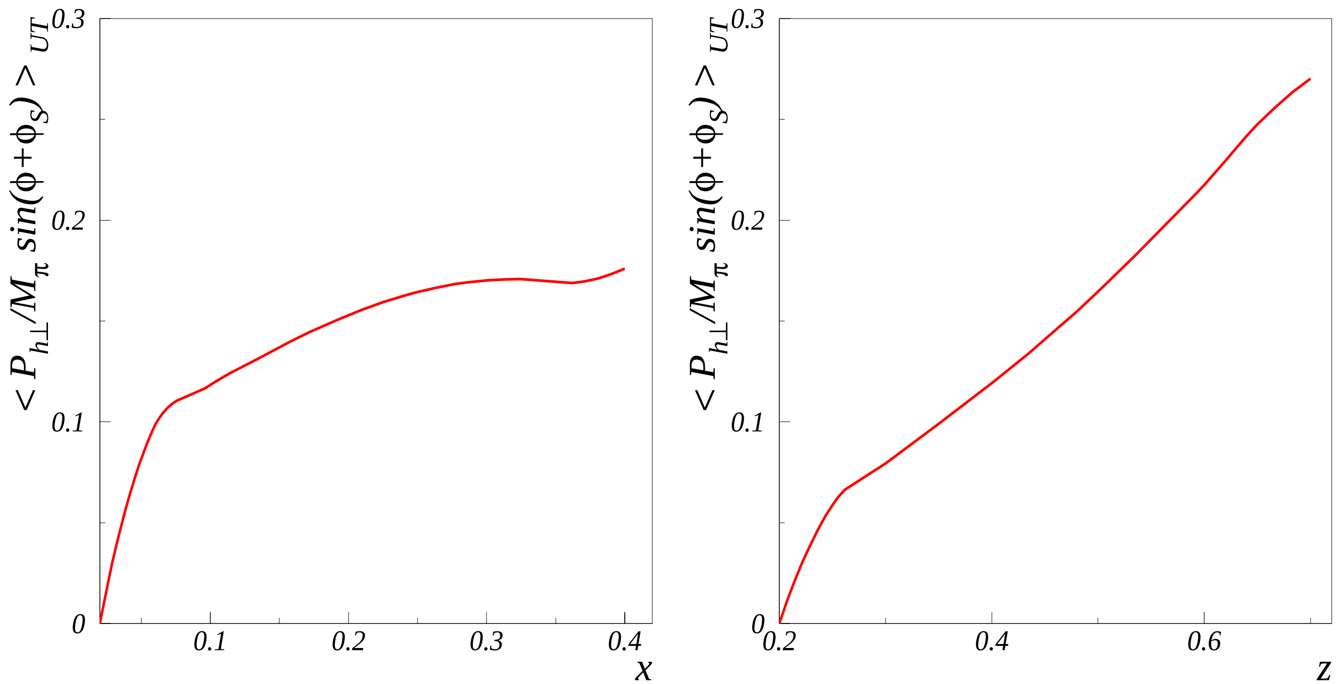


Collins Asymmetry

- Convolution of two chiral-odd (both T-odd and T-even) structures,

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

$$= |S_T| \frac{2(1-y) \sum_q e_q^2 h_1(x) z H_1^{\perp(1)}(z)}{(1+(1-y)^2) \sum_q e_q^2 f_1(x) D_1(z)}.$$

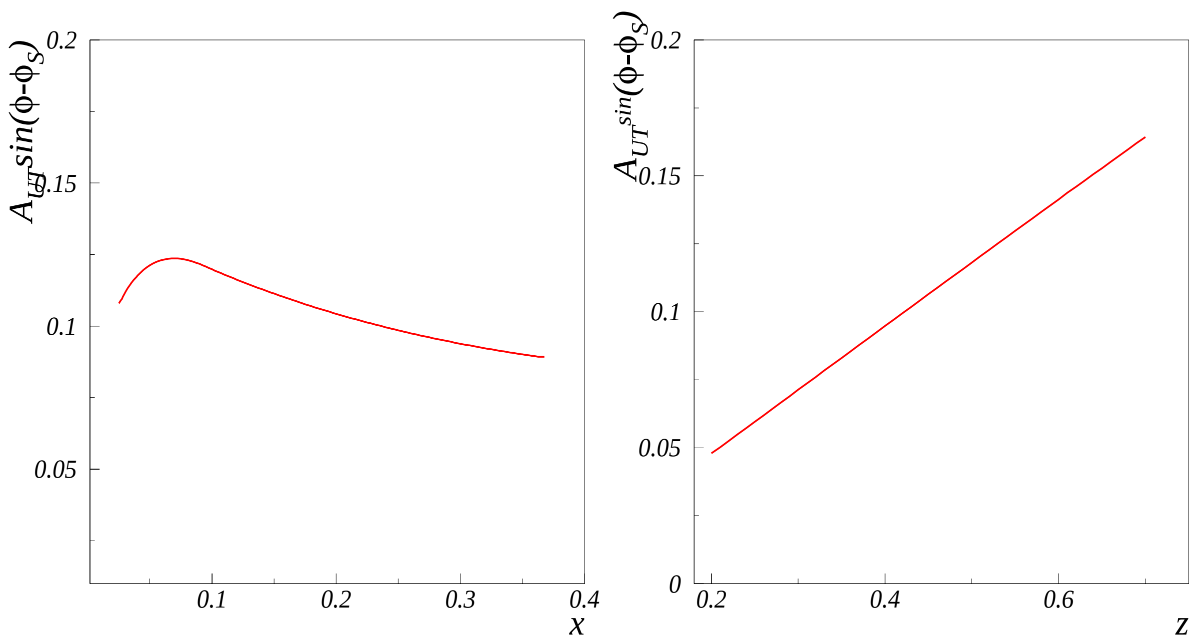


Estimates for Sivers Asymmetry

$$\langle \frac{|P_{h\perp}|}{M} \sin(\phi - \phi_S) \rangle_{UT} = \frac{\int d^2 P_{h\perp} \frac{|P_{h\perp}|}{M} \sin(\phi - \phi_S)\, d\sigma}{\int d^2 P_{h\perp}\, d\sigma}$$

$$= \frac{(1 + (1-y)^2) \sum_q e_q^2 f_{1T}^{\perp(1)}(x) z D_1^q(z)}{(1 + (1-y)^2) \sum_q e_q^2 f_1(x) D_1(z)},$$

where $A_{UT}^{\sin(\phi-\phi_S)} \approx \frac{M}{\langle P_{h\perp} \rangle} \langle \frac{|P_{h\perp}|}{M} \sin(\phi - \phi_S) \rangle_{UT}$



Combined $\cos 2\phi$ asymmetry

Effects that vanish as $k_\perp^2/Q^2$ important at small and moderate values of $Q^2 \Rightarrow \langle\cos 2\phi\rangle_{UU}$ results from the ordinary kinematic twist-4 T-even and leading double T-odd effects,

Gamberg, Goldstein, Oganessyan:DIS-2003-hep/ph-arXiv

$$\langle\cos 2\phi\rangle_{UU} = \frac{2\frac{\langle k_\perp^2\rangle}{Q^2}(1-y)f_1(x)D_1(z) + 8(1-y)h_1^{\perp(1)}(x)H_1^{\perp(1)}(z)}{\left[1+(1-y)^2+2\frac{\langle k_\perp^2\rangle}{Q^2}(1-y)\right]f_1(x)D_1(z)}$$

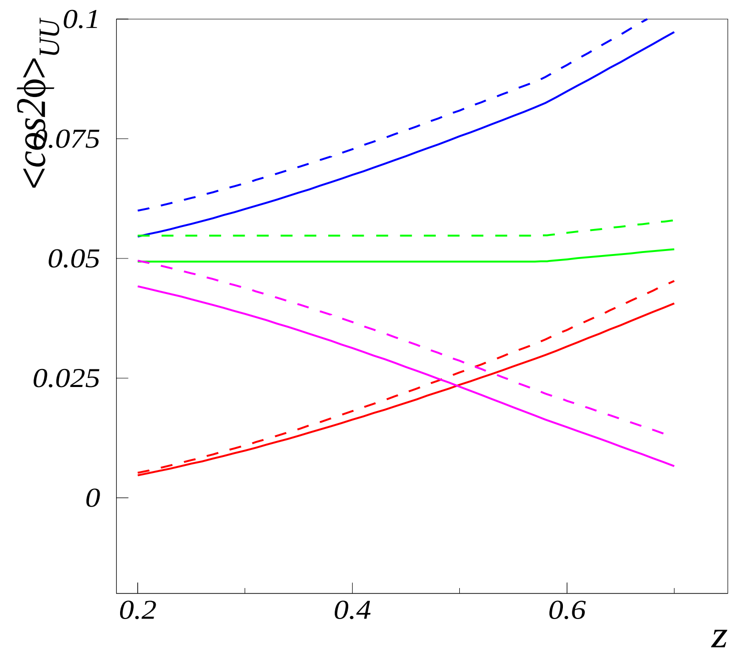
The z-dependences of the asymmetry The full and dashed curves correspond to the asymmetry with and without $k_\perp^2/Q^2$ term in the denominator, respectively.

Red $\Rightarrow$ T-odd term.

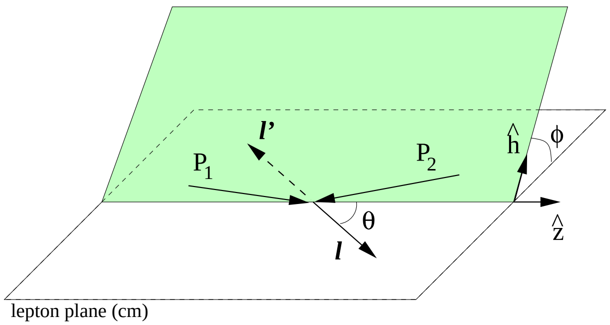
Green $\Rightarrow$ T-even term

Blue $\Rightarrow$ sum of them

Magenta $\Rightarrow$ difference



Unpolarized DRELL YAN $cos2\phi$



$$\bar{p} + p \to \mu^- \mu^+ + X$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1 + \lambda\cos^2\theta + \mu\sin^2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right) \quad (2)$$

Angle refer to the lepton pair orientation in their rest frame relative to the boost direction and the initial hadron's plane.

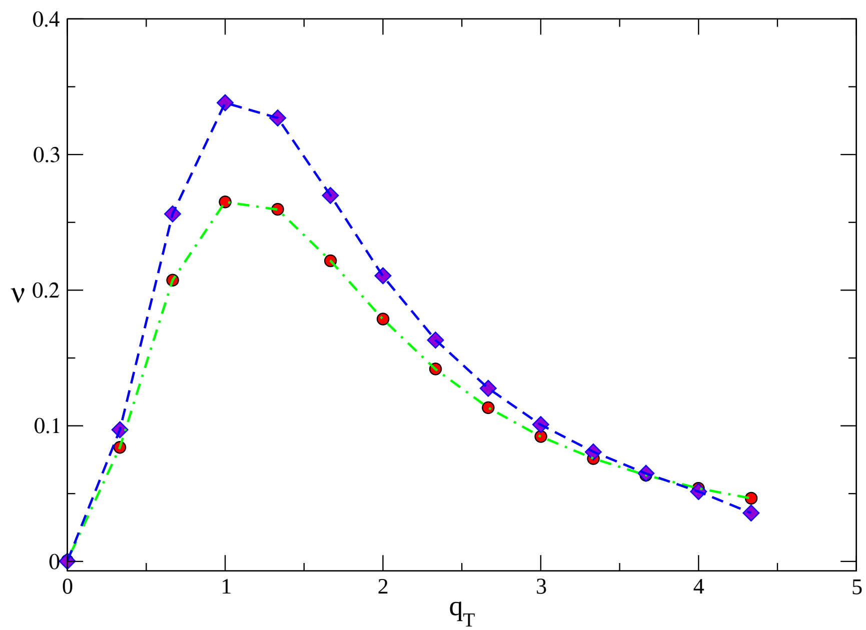
- BoerPRD: 1999 $\cos 2\phi$ azimuthal asymmetry depends on the T-odd distribution $h_1^{\perp}$

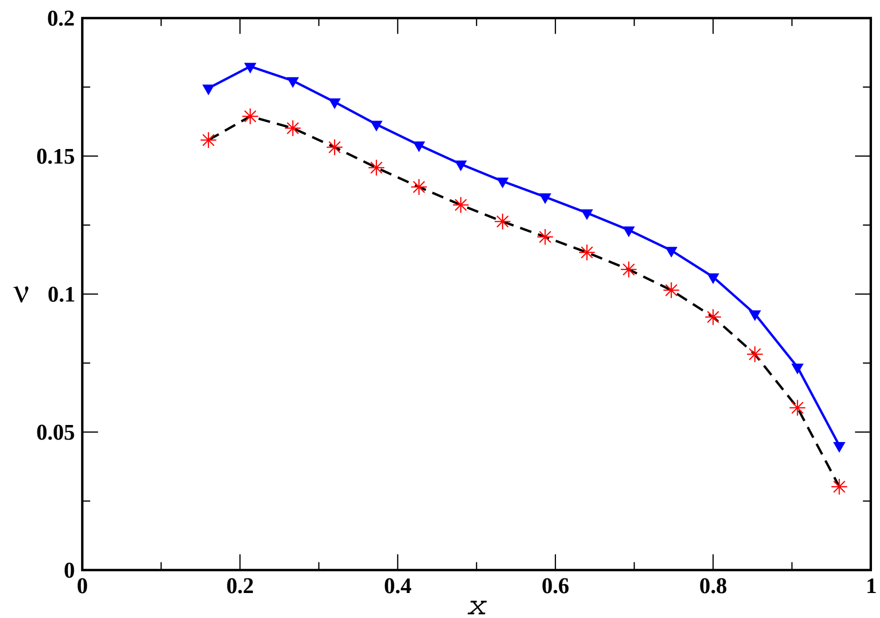
$$\nu = \frac{2\sum_a e_a^2 \mathcal{F}\left[(2\boldsymbol{p}_\perp\cdot\boldsymbol{k}_\perp - \boldsymbol{p}_\perp\cdot\boldsymbol{k}_\perp)\frac{h_1^{\perp}(x,\boldsymbol{k}_T)\bar{h}_1^{\perp}(\bar{x},\boldsymbol{p}_T)}{M_1 M_2}\right]}{\sum_{a,\bar{a}} e_a^2 \mathcal{F}[f_1\bar{f}_1]} \quad (3)$$

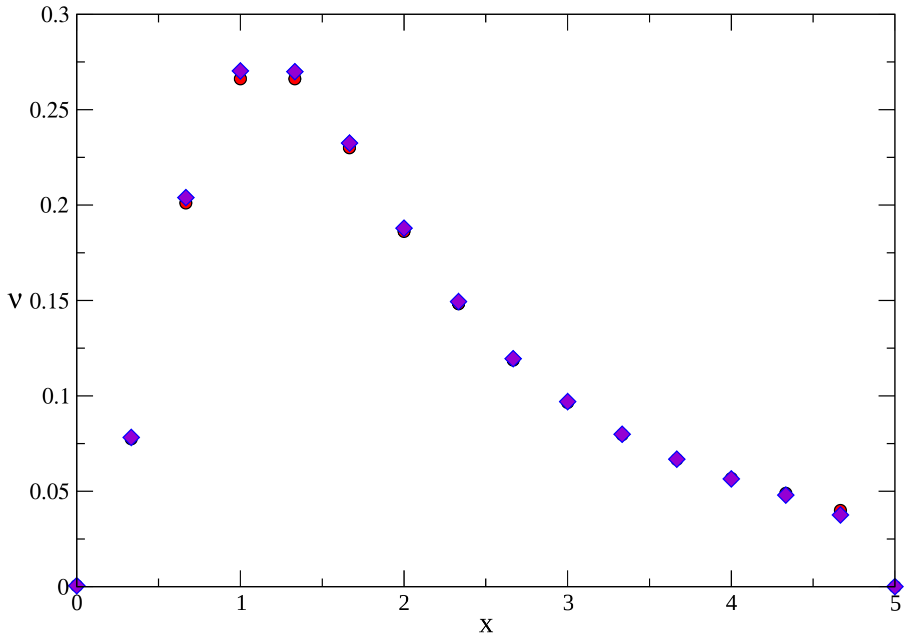
Convolution integral $\mathcal{F} \equiv \int d^2\boldsymbol{p}_\perp d^2\boldsymbol{k}_\perp \delta^2(\boldsymbol{p}_\perp + \boldsymbol{k}_\perp - \boldsymbol{q}_\perp) f^a(x,\boldsymbol{p}_\perp)\bar{f}^a(\bar{x},\boldsymbol{k}_\perp)$.
Higher twist comes in Collins SoperPRD: 1977

$$\nu = \frac{2\sum_a e_a^2 \mathcal{F}\left[(2\boldsymbol{p}_\perp\cdot\boldsymbol{k}_\perp - \boldsymbol{p}_\perp\cdot\boldsymbol{k}_\perp)\frac{h_1^{\perp}(x,\boldsymbol{k}_T^2)\bar{h}_1^{\perp}(\bar{x},\boldsymbol{p}_T)}{M_1 M_2} + T_4(x,\bar{x},\boldsymbol{k}_T,\boldsymbol{p}_T;[f_1\bar{f}_1])\right]}{\sum_{a,\bar{a}} e_a^2 \mathcal{F}[f_1\bar{f}_1]} \quad (4)$$

- Gamberg, Goldstein higher twist... In prep
- $s = 50\ GeV^2$ $x = 0.2 - 1.0$, $q = 2.5 - 5.0\ GeV$, $s = 500 GeV^2$, $x = 0.2 - 1.0$, and $q = 4.0 - 8.6\ GeV$



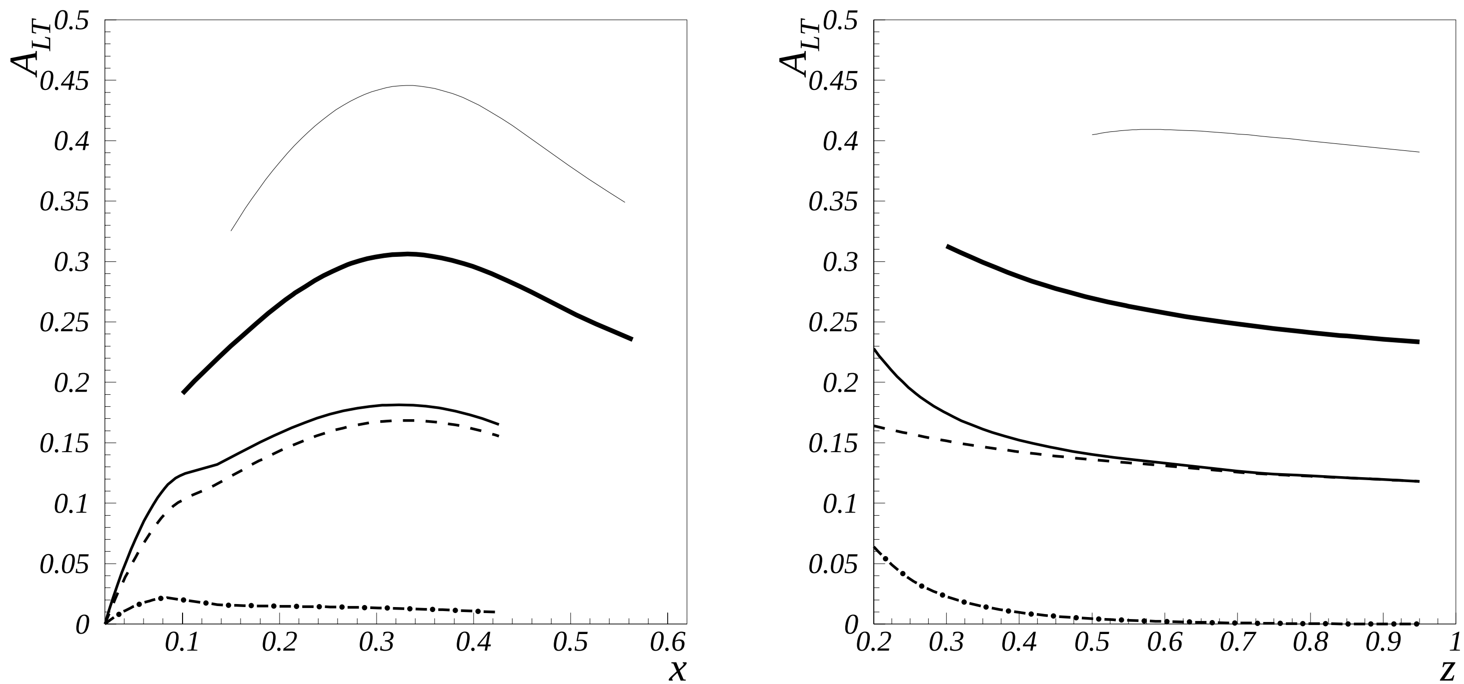




0.3
0.25
0.2
ν 0.15
0.1
0.05
0
0
1
2
3
4
5
x

⋆ SIDIS:Jaffe and Ji PRL:1993 encountered at twist three level Estimate of this effect, Gamberg, Hwang, Oganessyan PLB:2004

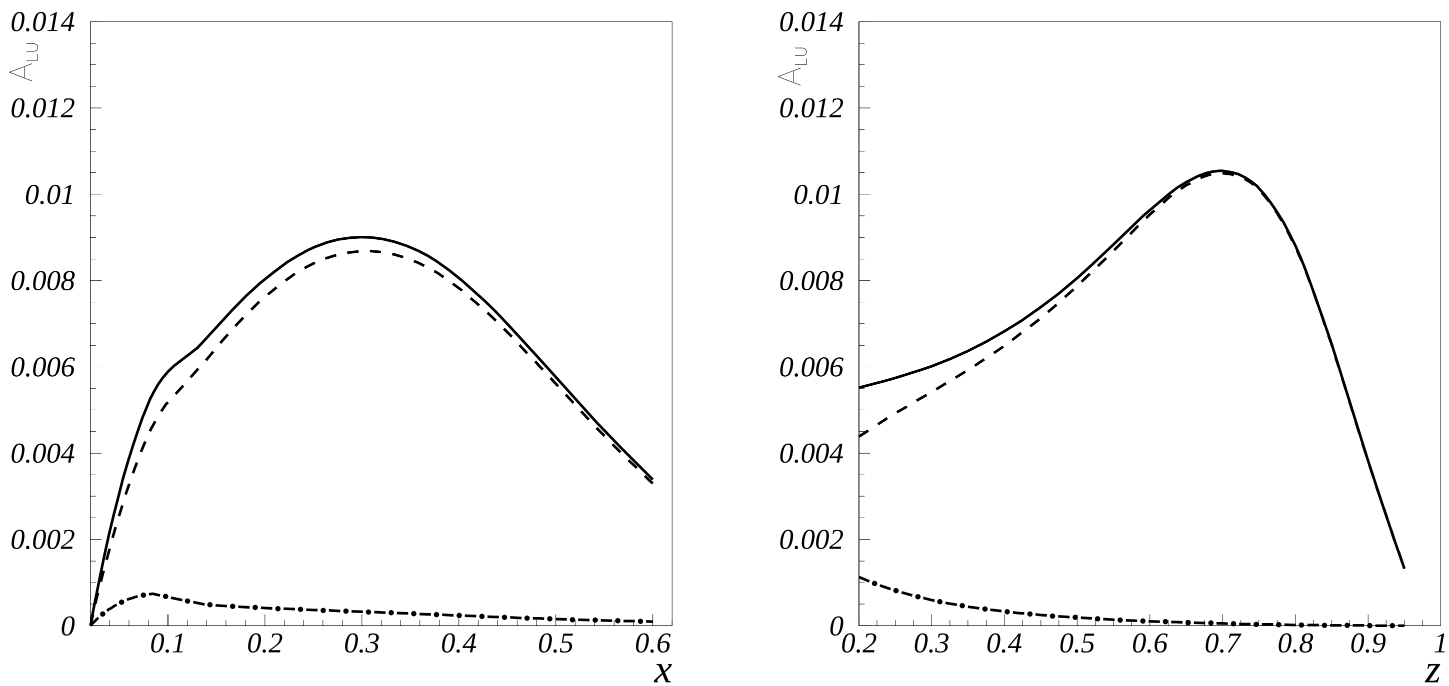
$$A_{LT} = \frac{\lambda_e |\boldsymbol{S}_T| \sqrt{1-y}\, \frac{4}{Q} \left[M\, x\, g_T(x) D_1(z) + M_h\, h_1(x) \frac{E(z)}{z} \right]}{\frac{[1+(1-y)^2]}{y}\, f_1(x) D_1(z)}$$



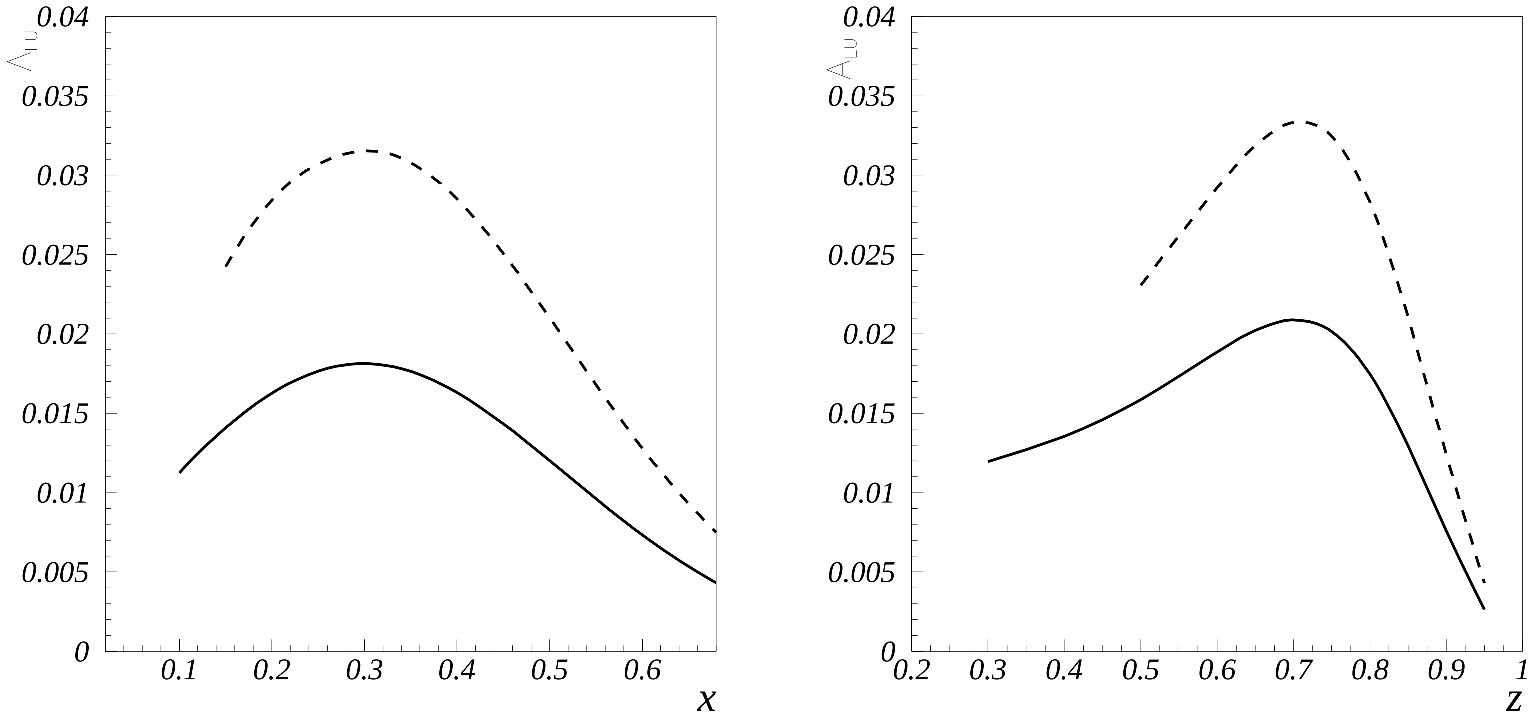
A_{LT} for π^+ production function of x and z at 27.5 GeV energy. The dashed and dot-dashed curves correspond contributions of the two terms of above respectively, and the full curve is the sum. The thin curve corresponds to 6 GeV and the thick curve to 12 GeV energies respectively.

★ Bean Asymmetry Estimate of this effect, Gamberg, Hwang, Oganessyan PLB:2004

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



A_{LU} for π^+ production as a function of x and z at 27.5 GeV energy. The dashed and dot-dashed curves correspond to contribution of the first and second terms of above equation respectively, and the full curve is the sum of the two



Also F. Yuan, PLB: 2004. Metz and Schleigel, hep-ph/0403182, Bacchetta *et al* hep-ph/0405154.

SUMMARY

- The angular correlations in semi-inclusive DIS are considered from the stanpoint of "rescattering" mechanism which generate T-odd, intrinsic transverse momentum, $k_\perp$, dependent *distribution and fragmentation* functions at leading twist

- We have evaluated these functions by modeling the quark, spectator hadron verticies in a quark-diquark-hadron framework
- We have evaluated azimuthal and SSA with Gaussian "regularization" in $\langle k_\perp \rangle$

- Analyzed the leading twist contribution to the $\cos 2\phi$ azimuthal asymmetries . We considered the impact that novel T-odd distribution and fragmentation functions have on transversity of quarks within unpolarized nucleon

- We consider the implications that these T-odd distribution and fragmentation functions have in Sivers and Collins asymmetries

⋆ Azimuthal asymmetries and SSA measured at HERMES and COMPASS and in future JLAB *may* reveal the extent to which these leading twist T-odd effects are generating the data

- These experiments may point to the essential role played by quark transverse momentum and $T-$odd quark distributions and effects of higher twist