Transversity Properties of Quarks and Nucleons in SIDIS and Drell Yan

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RHIC SPIN Collaboration Meeting *INFN, Turin*

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

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Introductory Remarks: Transversity

- Transversity $"\delta q"$ as combinations of helicity states

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

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 $h_1^a(x) = \delta q^a(x)$

- First moment, tensor charge Jaffe & Ji, PRL:1991 $\int_0^1 \left(\delta q^a(x) - \delta \overline{q}^a(x)\right) dx = \delta q^a$

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

TRANSVERSITY:
Understood Context Parton Model in IMF

- Light Cone Rep. of "Good" Dirac Spinors (Kogut, Soper PRD:1970)

$$\psi_+(\xi^-) = \int d^2k_\perp dk^+ \sum_{s=1,2} \left\{ b_s(k)u(s)\mathrm{e}^{-ik^+\xi^-} + d_s^\dagger(k)v(s)\mathrm{e}^{ik^+\xi^-} \right\}$$

  $P_\pm \psi = \psi_\pm$
  projector of *good* $+$ (indept.) and bad - (dept.) light cone spinors

- Instead of diagonalizing free Hamiltonian w/r to HELICITY eigenstates: 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 the free-quark Hamiltonian and with $P_\pm$, is a *good* light cone operator

TRANSVERSITY BASIS

- Transverse Basis: $Q_{\top/\perp} = \frac{1}{2}\left(\mathbf{1} \mp \gamma_5 \gamma^{\perp}\right)$

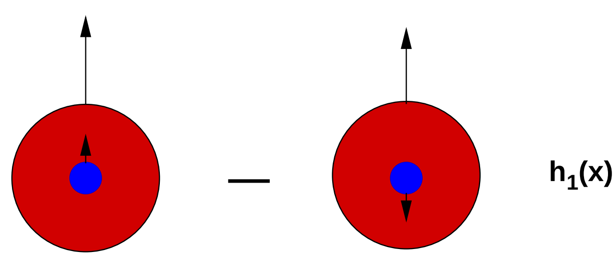
While $g_1(x)$ meaning is obscure

$$g_1(x) \;=\; \mathrm{Re}\frac{2}{x}\langle P\hat{\mathbf{e}}_3|b^{\dagger}_{\perp}(xP)b_{\top}(xP)|P\hat{\mathbf{e}}_3\rangle$$

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 clearly defined as the probability to find quark with spin polarized along transverse spin direction minus oppositely polarized case



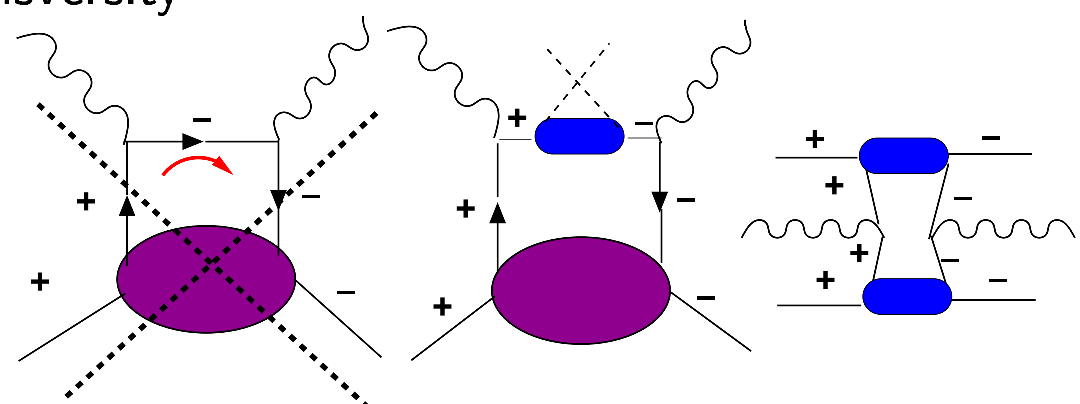
Theoretically among other things:

- ⋆ 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

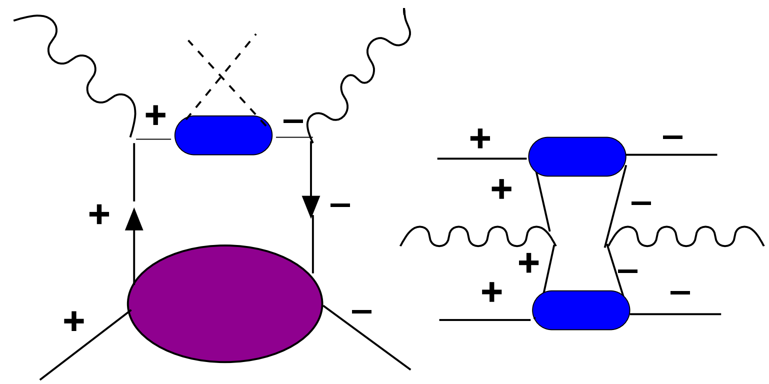
- Decouples leading twist DIS: Helicity of struck quark must flip to probe transversity chiral-odd
  $\Rightarrow$require chiral-odd partner
  $\Rightarrow$ and one or more hadrons
  involved in process probe transversity

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: Leading Twist

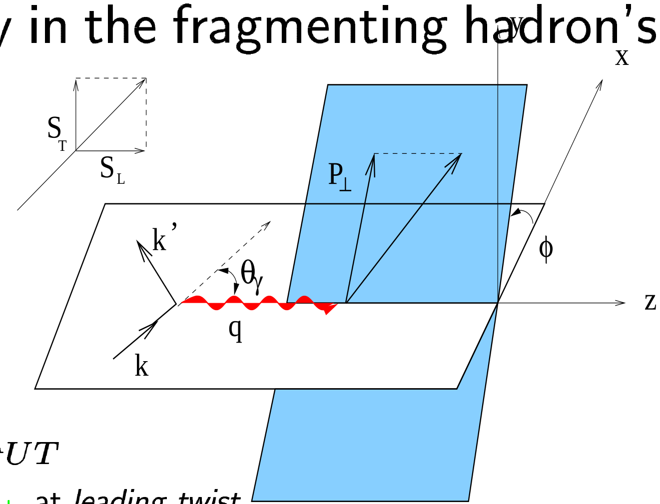
- Collins NPB:1993, Kotzinian NPB:1995, Mulders, Tangermann PLB:1995

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

  $P_{h\perp}$ - hadron transverse momentum

  ϕ, azimuth between $[k\ q]$ and $[P_h\ q]$ planes

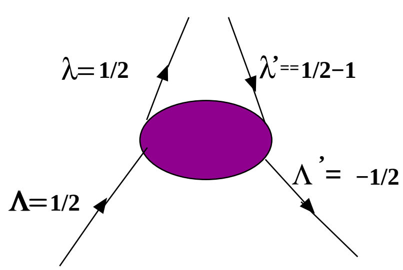
  ϕ_S, azimuth of the target spin vector



Here one considers cross sections differential in transverse momentum: SSA is not surpressed by inverse powers of the hard scale, ie in A_{UT} quarks in target, and current fragmentation region possess transverse momentum $p_\perp$, $k_\perp$ at ***leading twist***

Beyond Colinearity

The hadron helicity flip generated by quark orbital angular momentum, quarks have transverse momentum k_T in hadrons. Hadron helicity flip occurs by addition of quark orbital angular



$$\langle \frac{P_{h\perp}}{M_\pi} \sin(\phi + \phi_s) \rangle_{UT}$$

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

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

Color Gauge Invariance & 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

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

Hadronic Tensor

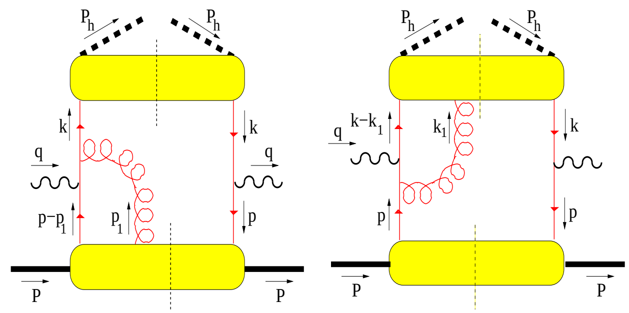
$$\begin{aligned} 2M\mathcal{W}^{\mu\nu}(q,P,P_h) \quad &= \quad \int d^2\boldsymbol{p}_T d^2\boldsymbol{k}_T \delta^2(\boldsymbol{p}_T + \boldsymbol{q}_T - \boldsymbol{k}_T) \\ &\mathrm{Tr}[\Phi(x_B,\boldsymbol{p}_T)\gamma^\mu\Delta(z_h,\boldsymbol{k}_T)\gamma^\nu] \,+\, (q\leftrightarrow -q\ ,\ \mu\leftrightarrow\nu)\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

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



- **T-odd Distribution Functions: Transversity Properties of quarks in Hadrons**
  Boer, Mulder, PRD 1998

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

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

Experimental status of SSAs

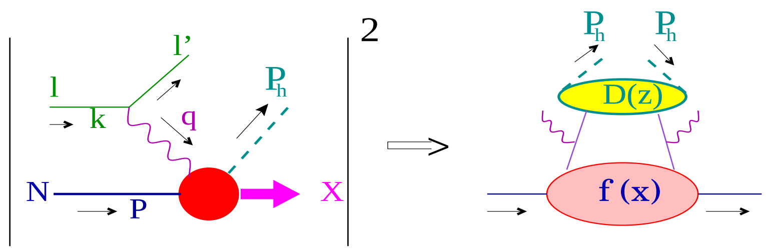
⋆ Dedicated transversity programs:

- $\ell\,\vec{p} \to \ell'\,\pi\,X$ DESY(HERMES), (1999, 2003....) See talk of Ralf Seidl
- $p^{\uparrow}\,p \to \pi\,X$ *RHIC* BNL(⋆STAR). See Talks of A. Ogawa and Les Bland
- CERN(COMPASS). See Talks at SPIN 2004
- JLAB-Hall A, B, C $\vec{\ell}\,\vec{p} \to \ell'\,\pi\,X$. See Talks at SPIN 2004

- Also, large SSA are observed in $P\,P^{\uparrow} \to \pi\,X$
  E704 Collaboration (1991)

NON-ZERO AZIMUTHAL ASYMMETRIES

- Origins/Mechanisms
  - ⋆ In the naive parton model all azimuthal asymmetries are zero at leading order
  - ⋆ However, both intrinsic k_T dependence & higher order in α_s PQCD generate azimuthal asymmetries



may arise from different mechanisms containing ordinary T-even soft parts:

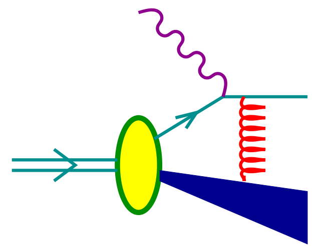
⋆ H. Georgi, H.D. Politzer, PRL:1978: pQCD first order α_s

⋆ R.N. Cahn, PLB: 1978; PRD: 1989; Chay, Ellis, Stirling, PRD: 1991, Oganessyan *et al.*, ZPC: 1998

Intrinsic $k_\perp$ & pQCD expansion in α_s

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

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)

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

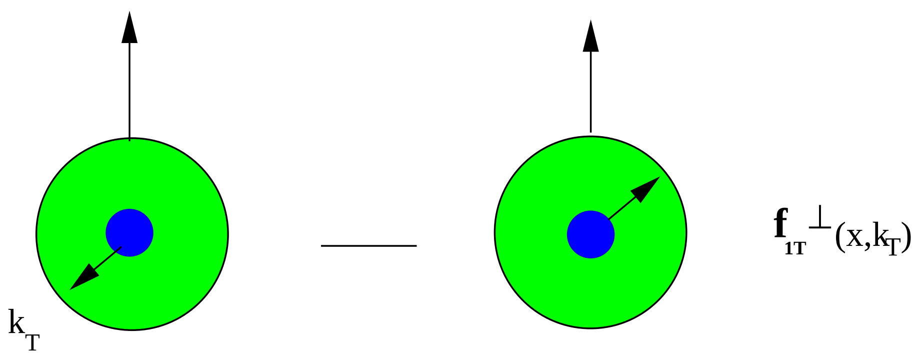
$$\mathcal{G}_{[\xi,\infty]}=\mathcal{G}_{[\xi_T,\infty]}\mathcal{G}_{[\xi^-,\infty]}, \quad \text{where} \quad \mathcal{G}_{[\xi^-,\infty]}=\mathcal{P}exp(-ig\int_{\xi^-}^{\infty}d\xi^- A^+)$$

- Demnstrates that BHS calculated Sivers Function, $f_{1T}^\perp(x,k_\perp)|_{\rm SDIS}$
  In Singular gauge, $A^+=0$, effect remains

- Collins, PLB: 2002, modifies earlier claim of trivial Sivers Effect
  $f_{1T}^\perp(x,k_\perp)|_{\rm SDIS}=-f_{1T}^\perp(x,k_\perp)|_{\rm DY}$

Sivers Asymmetry in SIDIS

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



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

Reaction Mechanism explained as FSI

⋆ See Star and HERMES Data

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, $f_{1T}^{\perp}$, $h_1^{\perp}$

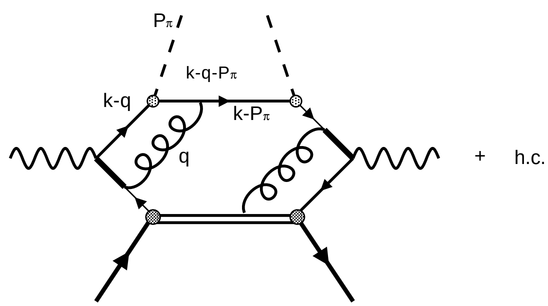
$$
\begin{aligned}
d\sigma_{\lambda,S} \quad &\propto \quad f_1 \otimes D_1 + \frac{k_T}{Q} f_1 \otimes D_1 \cdot \cos\phi \\
&+ \quad \left[\frac{k_T^2}{Q^2} f_1 \otimes D_1 + h_1^{\perp} \otimes H_1^{\perp} \right] \cdot \cos 2\phi \\
&+ \quad |S_T| \cdot h_1 \otimes H_1^{\perp} \cdot \sin(\phi + \phi_S)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

- Also the case in Drell Yan ... in progress. See talk of Goldstein Trento June 2004, Gamberg Marseille HiX Workshop leading and higher twist analysis. Also Boer PRD 1999 for leading twist T-odd contribution.

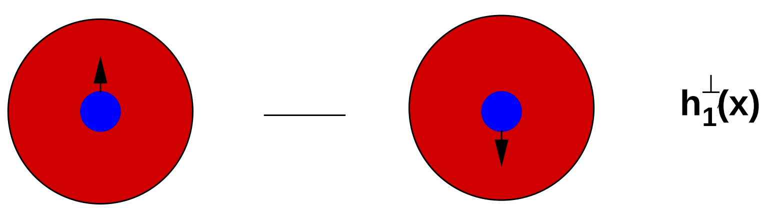
Rescattering Mechanism to Generate T-Odd Function $h_1^\perp$

Goldstein, Gamberg–ICHEP-proc., Amsterdam: 2002, hep-ph/0209085

- $h_1^\perp$ Naturally defined 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 $f_{1T}^\perp(x, k_\perp)$,



Estimates of T-odd Contributions to Azimuthal Asymmetries at Leading Twist

$\cos 2\phi$ Asymmetry

⋆ 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;

Boer, Brodsky, Hwang, PRD: 2003

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

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

- Asymmetry involves weighted function

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

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

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

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

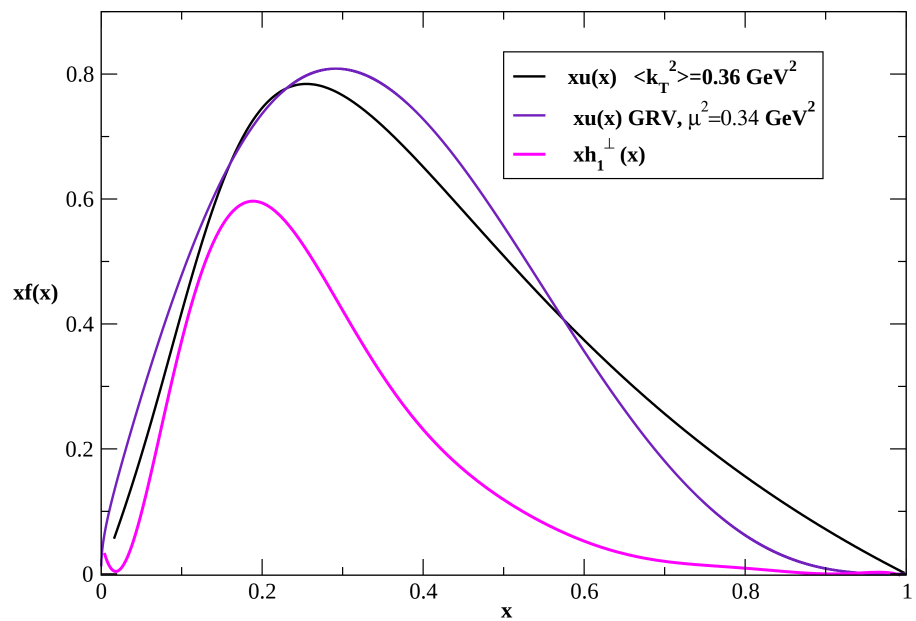
- Check approach: $\lim < k_\perp^2 > \to \infty$ Gaussian width goes to infinity, regain *log divergent* result

Unpolarized Structure Function

$$f(x) = \frac{g^2}{(2\pi)^2}\frac{b^2}{\pi^2}(1-x)$$

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

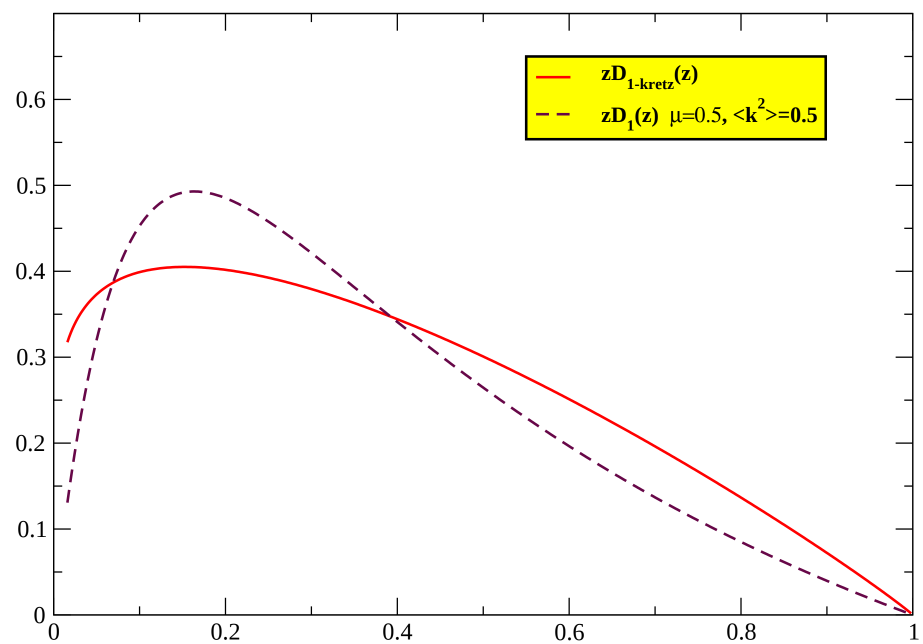
- ⋆ Normalization, $\int_0^1 u(x) = 2$
- Black curve- $xu(x)$
- Purple curve - $xu(x)$ from GRV
- Pink curve $xh_1^{\perp(u)}$



Pion Fragmentation Function

$$
\begin{aligned}
D_1(z) \quad = \quad & \frac{N'^2 f_{qq\pi}^2}{4(2\pi)^2} \frac{1}{z} \frac{(1-z)}{z} \left\{ \frac{m^2 - \Lambda'(0)}{\Lambda'(0)} \right. \\
& \left. - \left[2b' \left(m^2 - \Lambda'(0) \right) - 1 \right] e^{2b'\Lambda'(0)} \Gamma(0, 2b'\Lambda'(0)) \right\},
\end{aligned}
$$

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



Rescattering Mechanism for T-Odd Collins Function

Gamberg,Goldstein,Oganessyan hep-ph/0307139, PRD68,2003

- Gauge-link contribution to the Collins Function:

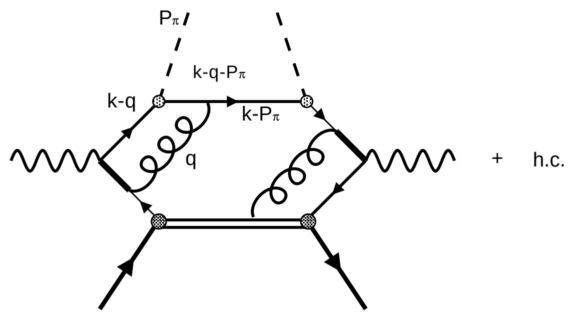


Figure depicts $h_1^{\perp} \star H_1^{\perp}\, \cos 2\phi$ asymmetry. The momenta flow to the quark-pion vertex is shown. The momentum q is the loop integration variable.

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

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

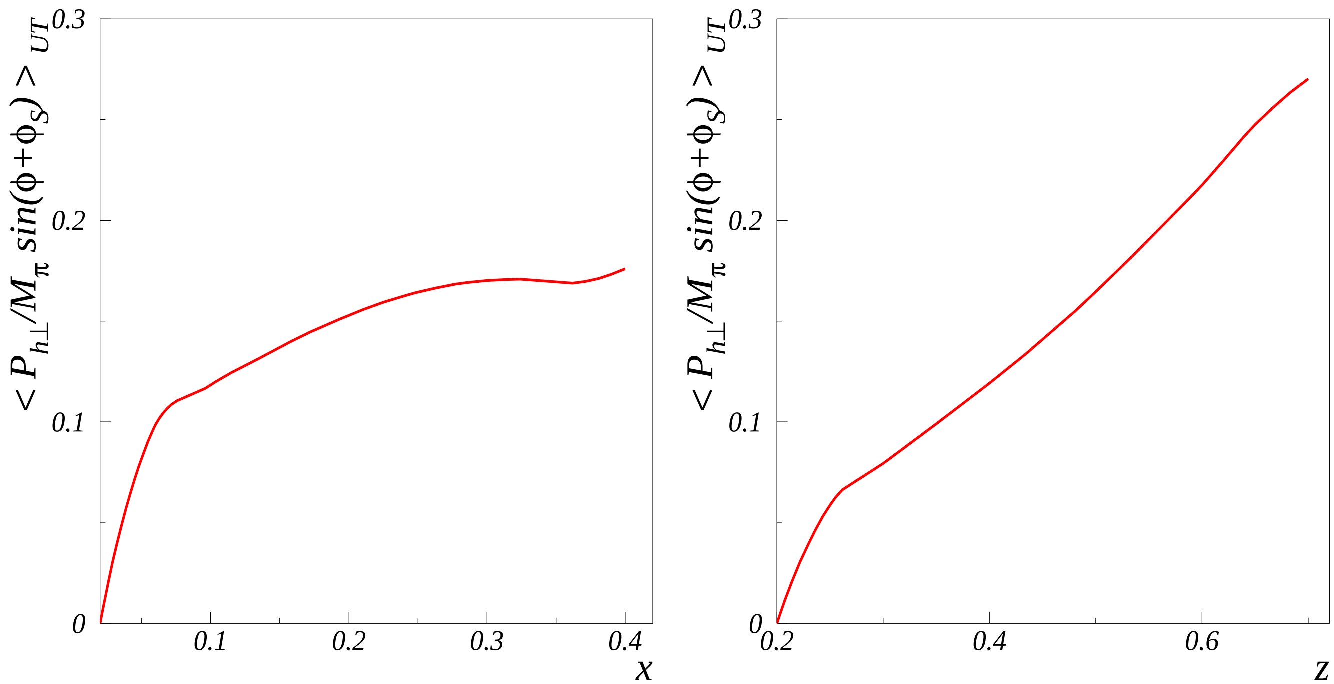
where, $\Lambda'(k_\perp^2) = k_\perp^2 + \frac{1-z}{z^2}M_\pi^2 + \frac{\mu^2}{z} - \frac{1-z}{z}m^2$

Collins Asymmetry

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

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

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



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

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

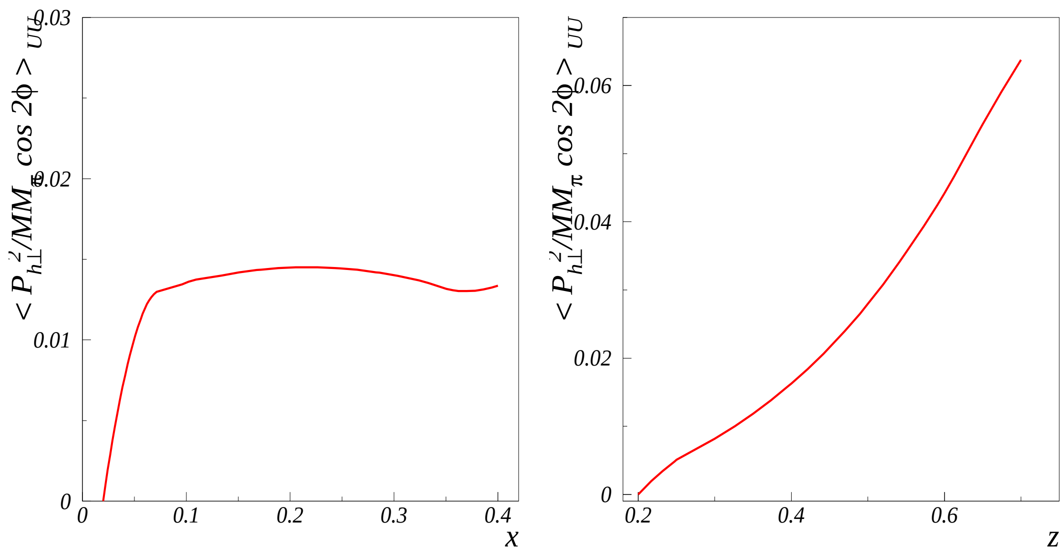
Gamberg, Goldstein, Oganessyan PRD 2003

For the HERMES kinematics

1 GeV$^2 \leq Q^2 \leq 15$ GeV^2, 4.5 GeV $\leq E_\pi \leq 13.5$ GeV,

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

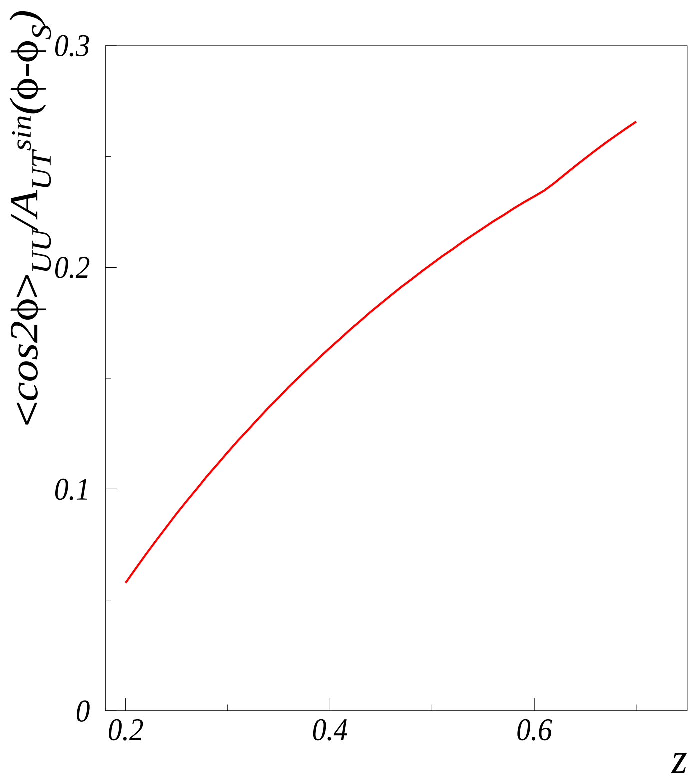
$$\langle \frac{|P^2_{h\perp}|}{M M_h} \cos 2\phi \rangle_{UU} = \frac{\int d^2 P_{h\perp} \frac{|P^2_{h\perp}|}{M M_h} \cos 2\phi \, d\sigma}{\int d^2 P_{h\perp} \, d\sigma} = \frac{8(1-y) \sum_q e_q^2 h_1^{\perp(1)}(x) z^2 H_1^{\perp(1)}(z)}{(1+(1-y)^2) \sum_q e_q^2 f_1(x) D_1(z)}$$



The T-odd $\cos 2\phi$ *vs* Sivers SSA

$$A = \frac{\langle \cos 2\phi \rangle_{UU}}{A_{UT}^{\sin(\phi-\phi_S)}} \sim z \cdot \frac{H_1^{\perp(1)}(z)}{D_1(z)},$$

Reflected in equality of $h_1^{\perp}$ and $f_{1T}^{\perp}$ functions in diquark model. Supports suggestion that the single-spin $\sin(\phi - \phi_S)$ Sivers and spin-independent $\cos 2\phi$ asymmetries are closely related in hard scattering processes

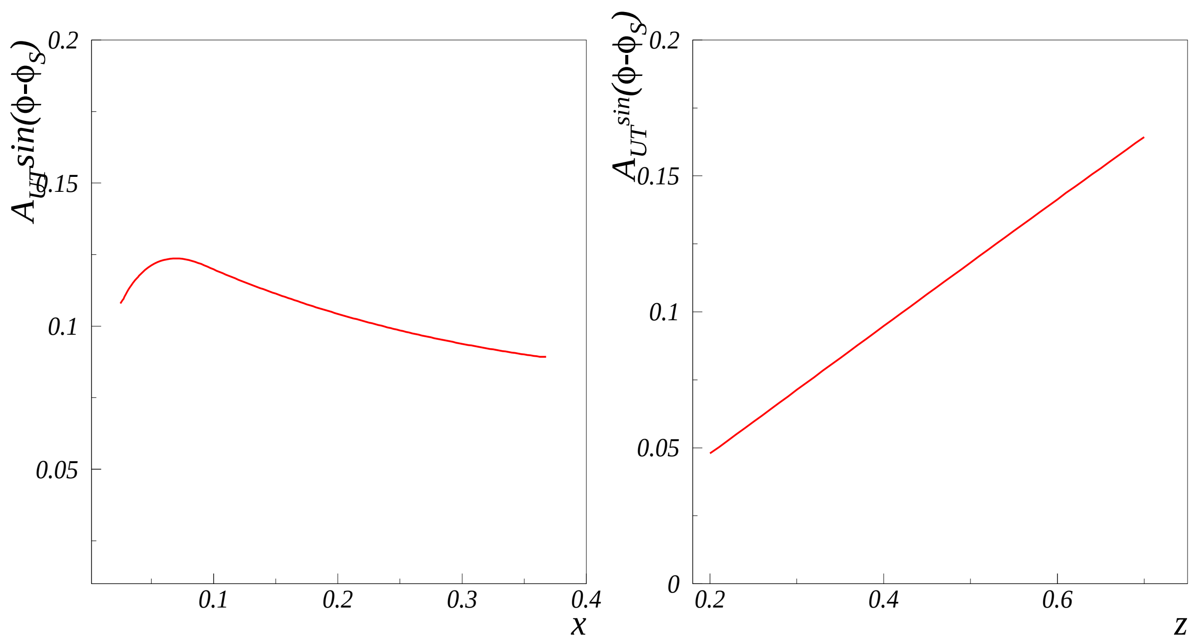


Estimates for Sivers Asymmetry

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

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

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

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

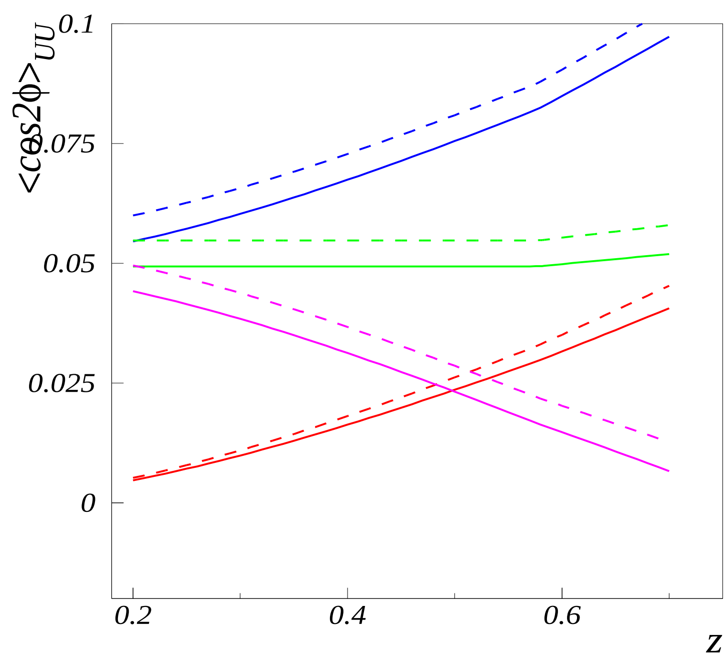
The z-dependences of the asymmetry The full and dashed curves correspond to the asymmetry with and without $k_\perp^2/Q^2$ term in the denominator, respectively.

Red $\Rightarrow$ T-odd term.

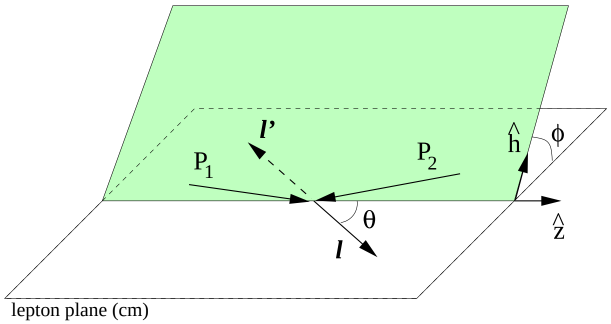
Green $\Rightarrow$ T-even term

Blue $\Rightarrow$ sum of them

Magenta $\Rightarrow$ difference



Unpolarized DRELL YAN $cos2\phi$



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

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

The angles refer to the lepton pair orientation in their rest frame relative to the boost direction and the initial hadron's plane. Asymmetry parameters, λ, μ, ν, depend on s, x, $m^2_{\mu\mu}$, q_T

Boer PRD: 1999, Collins Soper PRD: 1977

- Interesting that the $\cos 2\phi$ azimuthal asymmetry depends on the T-odd distribution $h_1^\perp$.

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

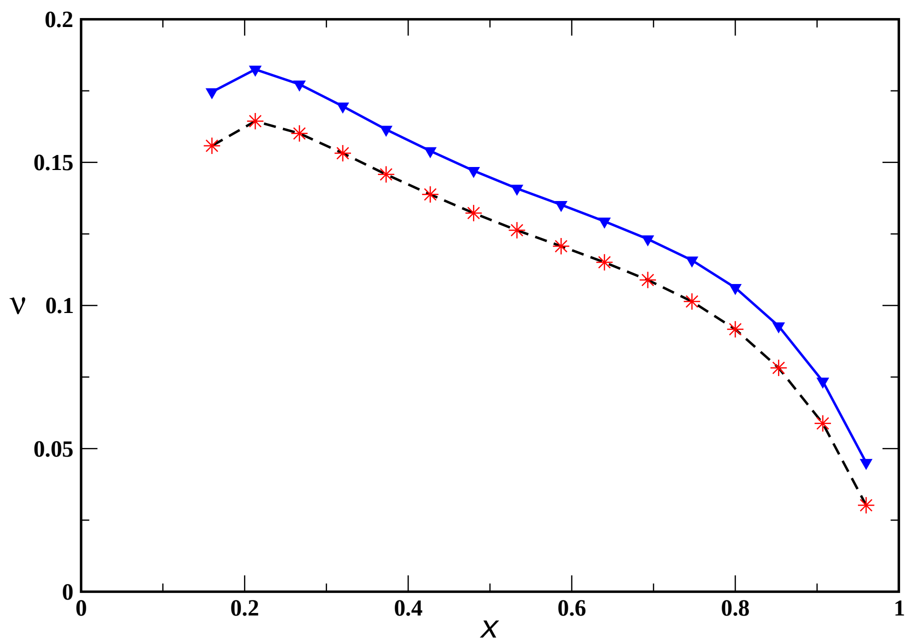
with the convolution integral

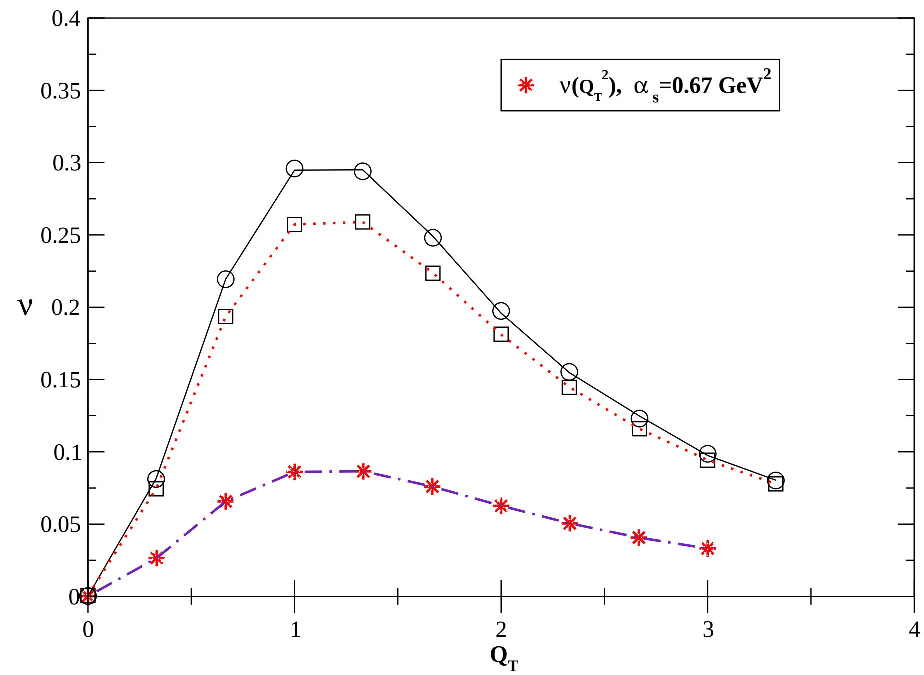
$$\mathcal{F} \equiv \int d^2\boldsymbol{p}_\perp d^2\boldsymbol{k}_\perp \delta^2(\boldsymbol{p}_\perp + \boldsymbol{k}_\perp - \boldsymbol{q}_\perp) f^a(x, \boldsymbol{p}_\perp)\bar{f}^a(\bar{x}, \boldsymbol{k}_\perp). \quad (3)$$

Higer twist comes in

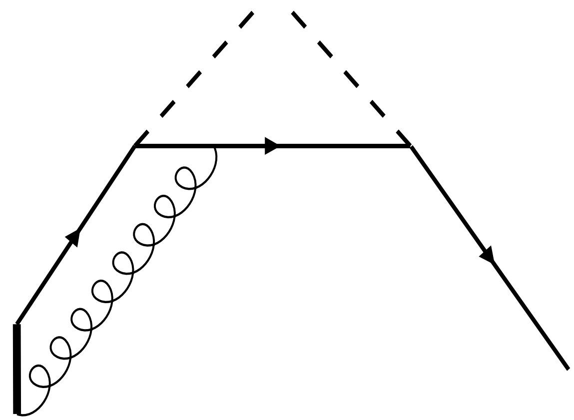
$$\nu = \frac{2\sum_a e_a^2 \mathcal{F}\left[(2\boldsymbol{p}_\perp \cdot \boldsymbol{k}_\perp - \boldsymbol{p}_\perp \cdot \boldsymbol{k}_\perp)\frac{h_1^\perp(x,\boldsymbol{k}_T^2)\bar{h}_1^\perp(\bar{x},\boldsymbol{p}_T)}{M_1 M_2} + T_4(x,\bar{x},\boldsymbol{k}_T,\boldsymbol{p}_T;[f_1\bar{f}_1])\right]}{\sum_{a,\bar{a}}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

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





On the Subject of other approachs see Bacchetta, Metz, Yang PLB2004



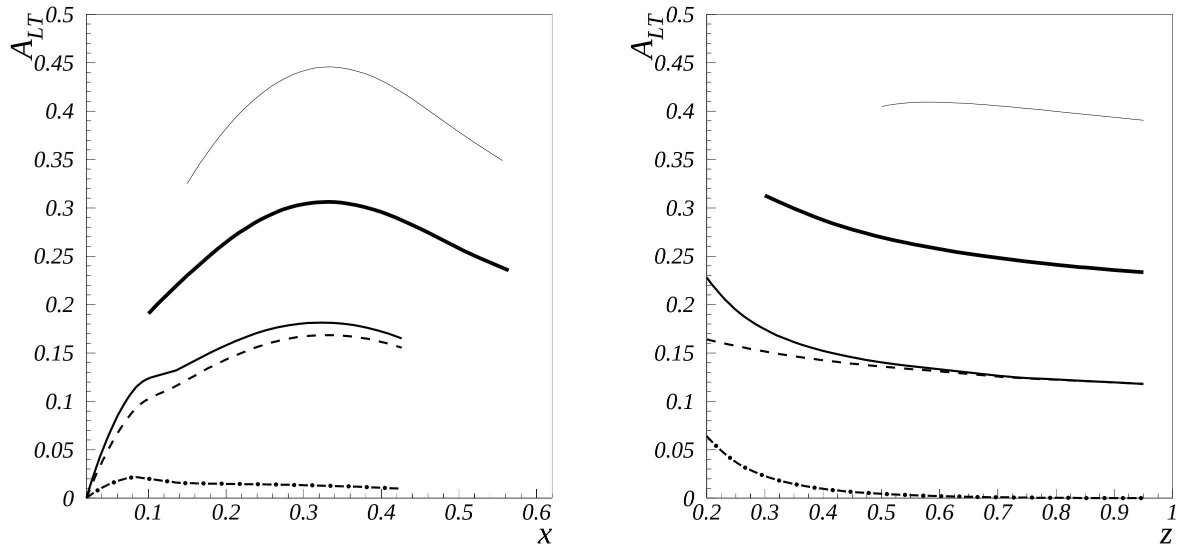
- Can mass corrections generate necessary phases?
- Must be careful about scales off shellness goes to on shell in deriving mass singularities or colinear singularities.
- Here we confront the “boundary” of non-perturbative physics with PQCD....

$$\log \frac{Q^2}{\mu^2}$$

See new work of Ji, Ma, Yuan hep-ph/0404183 and Collins and Metz ....

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

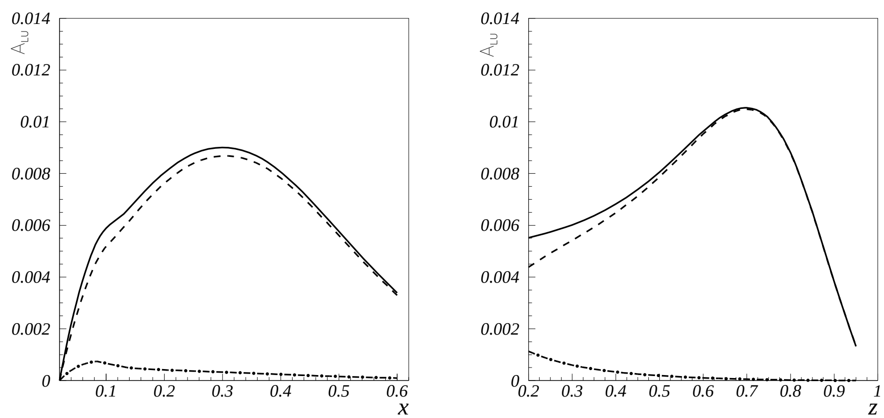
$$A_{LT} = \frac{\lambda_e |\boldsymbol{S}_T| \sqrt{1-y}\, \frac{4}{Q} \left[M\, x\, g_T(x) D_1(z) + M_h\, h_1(x) \frac{E(z)}{z} \right]}{\frac{[1+(1-y)^2]}{y}\, f_1(x) D_1(z)}$$



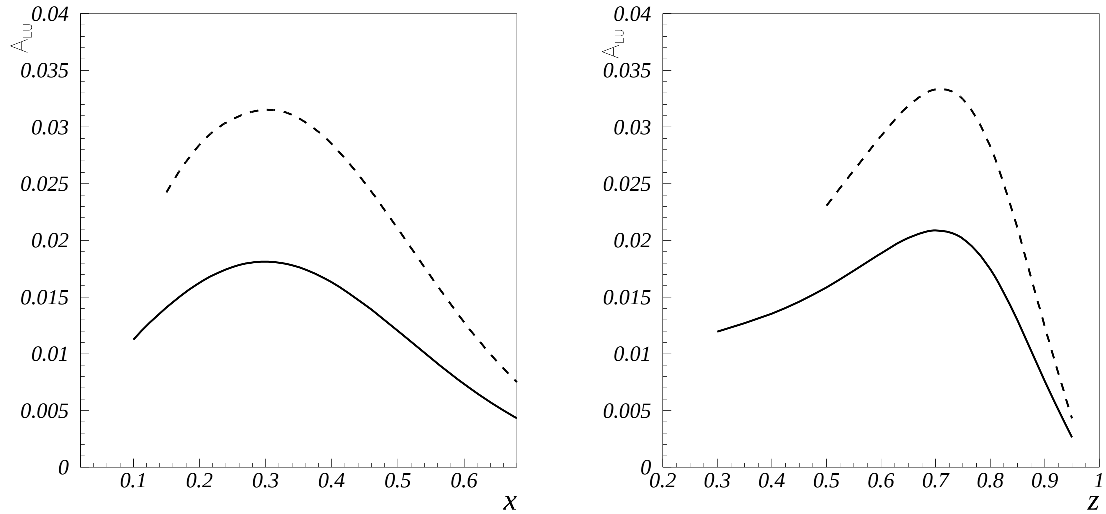
A_{LT} for π^+ production function of x and z at 27.5 GeV energy. The dashed and dot-dashed curves correspond contributions of the two terms of above respectively, and the full curve is the sum. The thin curve corresponds to 6 GeV and the thick curve to 12 GeV energies respectively.

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

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



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 $\langle k_\perp \rangle$ and addressed the Log divergence problem

- 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

$\star$ 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