Transversity Properties of Quarks and Hadrons in SIDIS and Drell Yan

Leonard Gamberg*

Division of Science, Penn State Berks

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- Remarks on SSA and AA role of p_T in QCD
- Role of Intrinsic $k_\perp$ in Understanding Transversity
- ⋆ Novel Transversity Properties in Hard Scattering
- ⋆ Reaction Mechanism-Rescattering: T-odd Structure and Fragmentation Functions
- ⋆ Estimates of the Collins and Sivers Asymmetries
- ⋆ Double T-odd $\cos 2\phi$ asymmetry in SIDIS and DY & higher twist
- ⋆ Beam Asymmetry
- Conclusions

*G. R. Goldstein, Tufts Univ. ,K.A. Oganessyan formerly *INFN-LNF* Frascati & Financial Co., NYC, and D.S. Hwang Sejong Univ, Kr

Transverse SSA (TSSA) and AZIMUTHAL ASYMMETRIES

- Origins/Mechanisms

  ⋆ Colinear approx TSSA vanishingly small at large scales and leading order α_s^0 : yet large experimental asymmetries

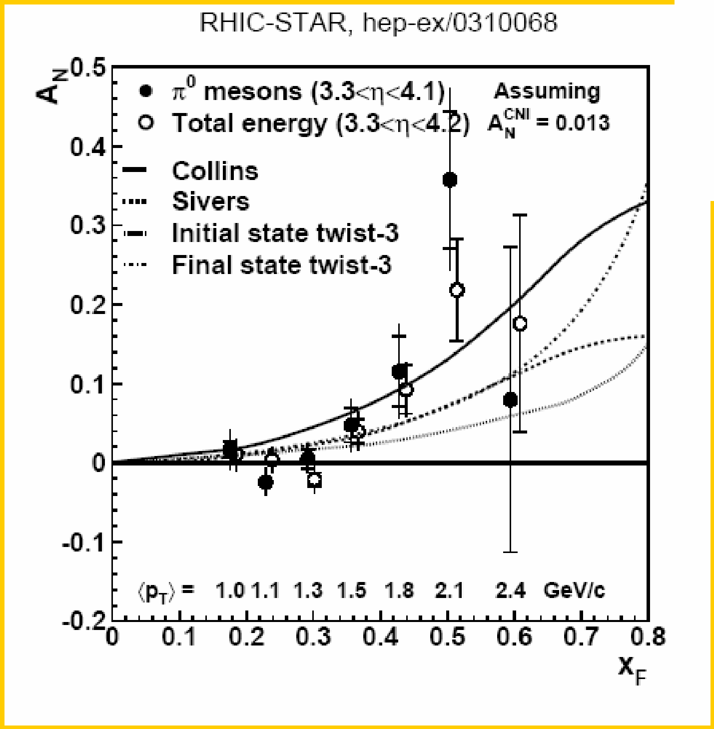
$$|\perp/\top\rangle = \frac{1}{\sqrt{2}}(|+\rangle \pm i|-\rangle) \Rightarrow A_N = \frac{d\hat{\sigma}^{\perp} - d\hat{\sigma}^{\top}}{d\hat{\sigma}^{\perp} + d\hat{\sigma}^{\top}} \sim \frac{2\, Im\, f^{*\,+} f^{-}}{|f^{+}|^2 + |f^{-}|^2}$$

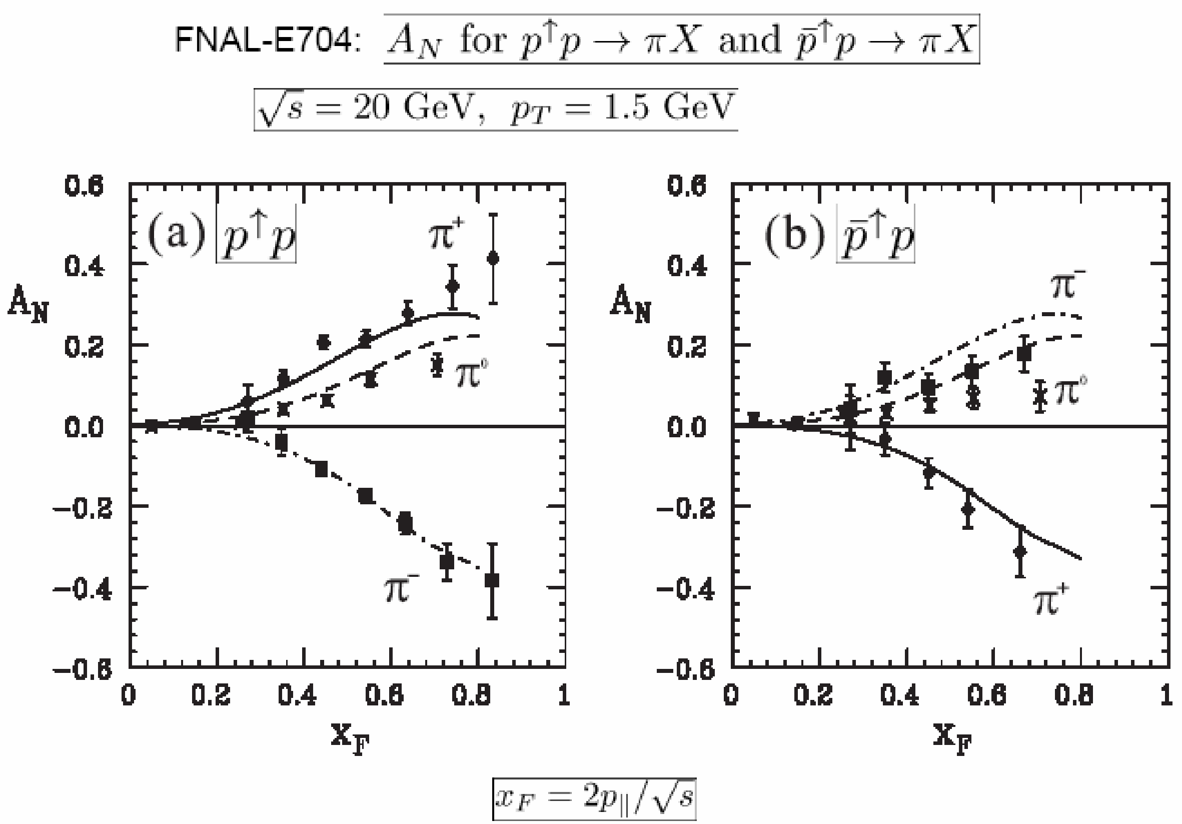
  ⋆ Requires Helicity flip at partonic level and realtive phase btwn helicity amps
  - Massless QCD conserves helicity and Born amplitudes are real
  ⋆ Interference loops-tree level Kane, Repko, PRL:1978: yield $A_N \sim m_q \alpha_s/\sqrt{s}$
  - $e.g.$ Inclusive Λ production ($pp \rightarrow \Lambda^{\uparrow} X$) PQCD contributions calculated Dharmartna & Goldstein PRD 1990

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

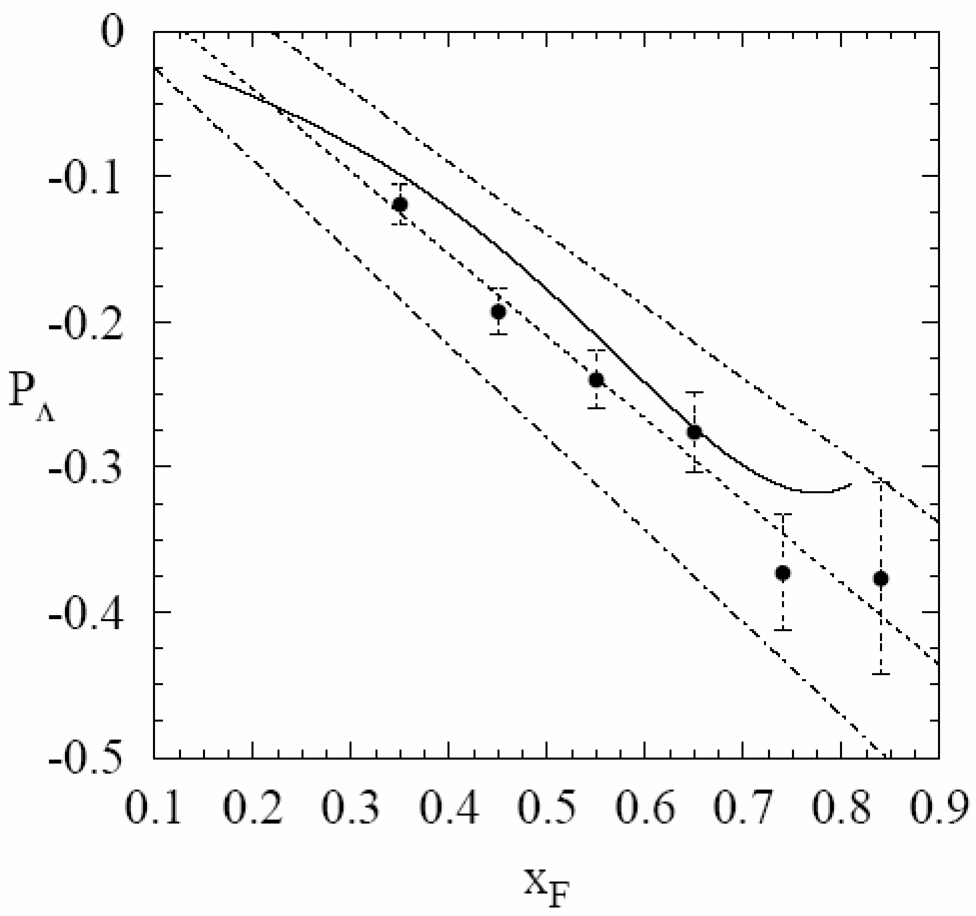
goes like $m_q \alpha_s/\sqrt{s}$ as predicted: m_q is the strange quark mass

STAR coll PRL 92 (2004)





FNAL E704 PLB (1991)

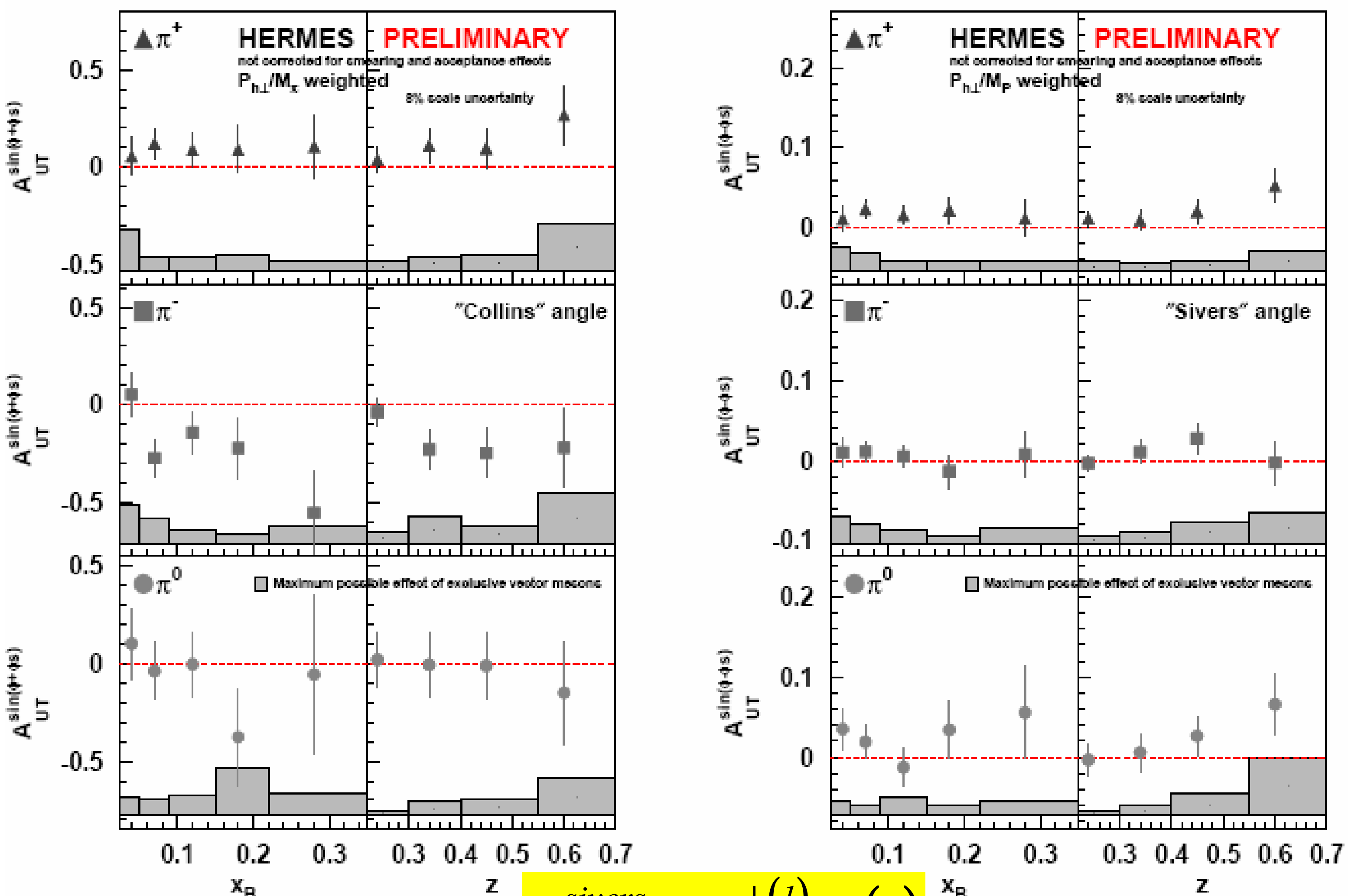


FNAL Heller *et al.* PRL (1983)

Inclusive Λ production

U. ELSCHENBROICH[a], G. SCHNELL[b], R. SEIDL[c]
(on behalf of the HERMES–Collaboration)

$$A_{UT}^{coll} \propto h_1(x) H_1^{\perp(1)}(z)$$

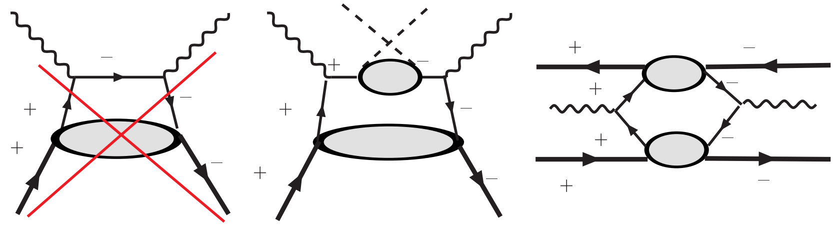


$$A_{UT}^{sivers} \propto f_{1T}^{\perp(1)} D_1(z)$$

: Asymmetries $A_{\mathrm{UT}}^{\sin(\phi \pm \phi_S)}$ for π^+, π^-, and π^0 depending on the kinematic variables x and z.

Helicity Flips Accommodated in Hard Scattering, "Transversity"

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



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

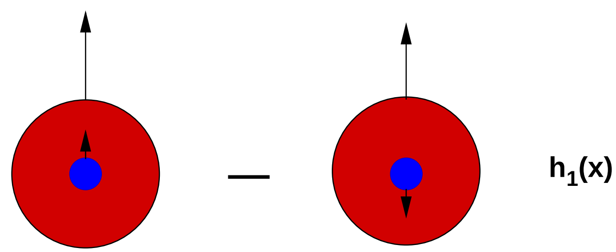
$$A_{TT}^{DY} = \frac{2\sin^2\theta\cos(\phi_1+\phi_2)}{1+\cos^2\theta}\frac{\sum_a e_a^2 h_1^a(x)\overline{h}_1^a(x)}{\sum_a e_a^2 f_1^a(x)\overline{f}_1^a(x)}$$

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

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

Theoretically among other things:

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



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

- Connection with spin structure revealed through Soffer's bound (Soffer, PRL:1995) & possible saturation/violation (Goldstein Jaffe Ji, PRD:1995) places bounds on leading twist distributions

$$\left|2\delta q^a(x, Q^2)\right| \leq q^a(x, Q^2) + \Delta q^a(x, Q^2)$$

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

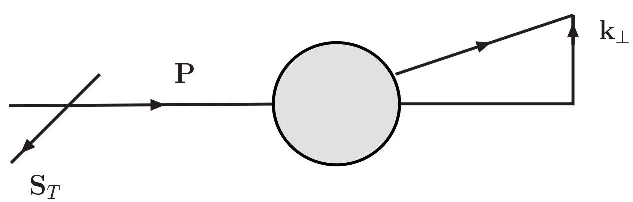
⋆ NLO analysis Martin & Vogelsang *et al*, PRD: 1998; indicates bound respected under evolution

T-Odd Correlations: Beyond Co-linearity

- However TSSA indicative T-odd correlations among spin and momenta e.g. $P\, P^{\perp} \to \pi\, X$ $\quad \boldsymbol{S}_T \cdot (\boldsymbol{P} \times \boldsymbol{k}_\perp)$

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

- Such an initial state effect proposed to account a left-right transverse SSA Sivers PRD 1990 in inclusive π production



- Soon after Collins NPB 1993 proposed T-odd correlation of transversally polarized fragmenting quark could furnishing a SSA in lepto-production $\ell\, \vec{p} \to \ell'\, \pi\, X$

- Final state effect: $\mathrm{s}_T \cdot (\boldsymbol{p} \times \boldsymbol{P}_{h\perp})$, where s_T is the spin of fragmenting quark, $\boldsymbol{p}$ is quark momentum and $\boldsymbol{P}_{h\perp}$ is transverse momentum produced pion

- Recent years Boer & Mulders and Co. incoporated $\boldsymbol{k}_\perp$ T-odd PDFs and FFs: relevant to hard scattering QCD leading twist Adopting Factorized Description
Levelt & Mulders, Mulders & Tangerman, NPB: 1994, 1996, See work of Ji, Ma, Yuan: 2004, Collins and Metz: 2005

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

Hadronic Tensor

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

where

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

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

T-Odd Contributions to TSSA and Azimuthal Asymmetries lepto-production

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

And T-Odd Contributions to TSSA and Azimuthal Asymmetries Drell Yan

SIDIS and Transversity: Leading Twist

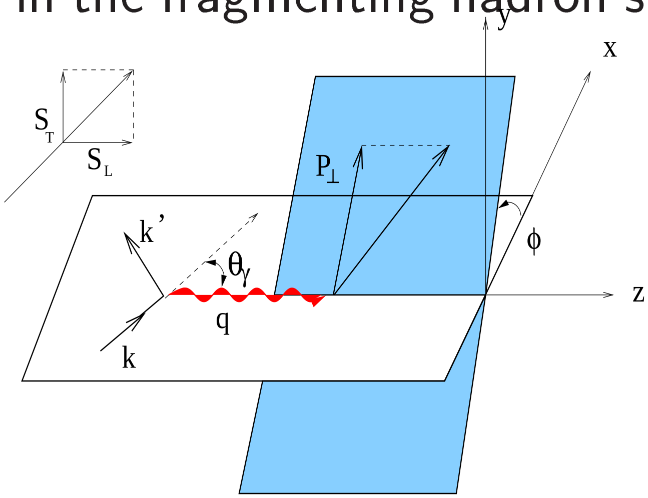
- Collins NPB:1993, Kotzinian NPB:1995, Mulders, Tangermann PLB:1995

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

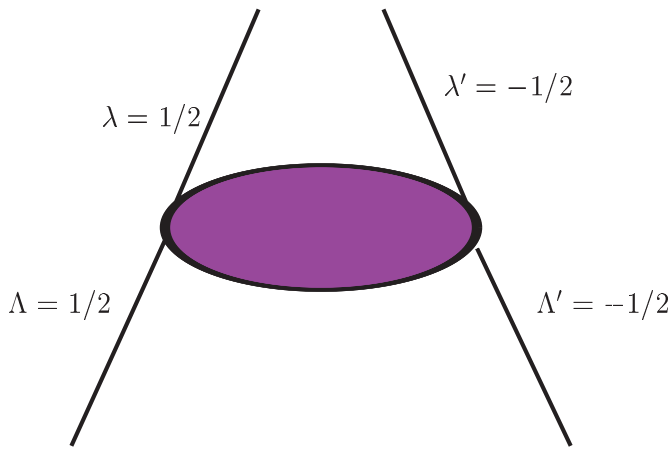
  $P_{h\perp}$ - hadron transverse momentum

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

  ϕ_S, azimuth of the target spin vector



One considers cross sections differential in transverse momentum: SSA not surpressed by inverse powers of the hard scale. Hadron helicity flip furnished by orbital angular momentum, quarks have $\boldsymbol{k}_\perp$

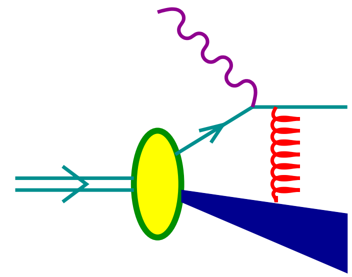


$$\langle \frac{P_{h\perp}}{M_\pi} \sin(\phi + \phi_s) \rangle_{UT}$$

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

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

Rescattering T-Odd Contributions to Asymmetries



PLB: 2002 Brodsky, Hwang, and Schmidt demonstarate 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 (Collins,Soper NPB: 1982)

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

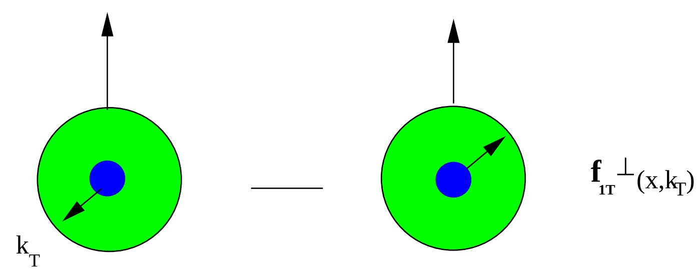
$$\mathcal{G}_{[\xi,\infty]} = \mathcal{G}_{[\xi_T,\infty]}\mathcal{G}_{[\xi^-,\infty]}, \quad \text{where} \quad \mathcal{G}_{[\xi^-,\infty]} = \mathcal{P}exp(-ig\int_{\xi^-}^{\infty} d\xi^- A^+)$$

- Demonstrates that BHS calculated Sivers Function, $f_{1T}^{\perp}(x,k_\perp)|_{\rm SDIS}$
  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:
  (Sivers PRD: 1990, Anselmino & Murgia PLB: 1995 ...)



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

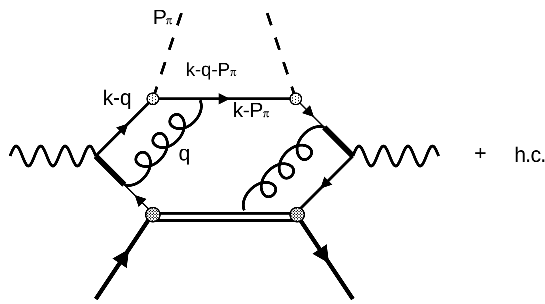
Reaction Mechanism explained as FSI

⋆ See Star and HERMES Data

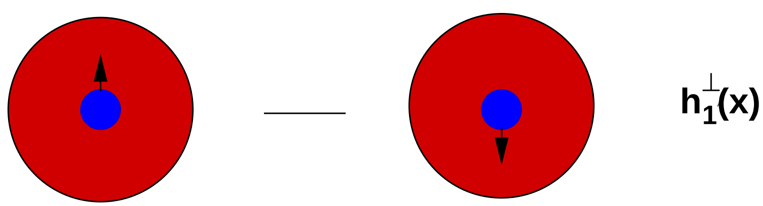
Rescattering Mechanism to Generate T-Odd Function $h_1^\perp$

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 Contribution in Azimuthal Asymmetries Drell Yan (GSI program) and SIDIS

$\cos 2\phi$ 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; Gamberg, Goldstein, Oganessyan 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

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

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

$$h_1^\perp(x,k_\perp) \quad = \quad \frac{e_1 e_2 g^2}{2(2\pi)^4}\frac{b^2}{\pi^2}\frac{(m+xM)(1-x)}{\Lambda(k_\perp^2)}\frac{1}{k_\perp^2}\mathcal{R}(k_\perp^2,x) \tag{1}$$

with

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

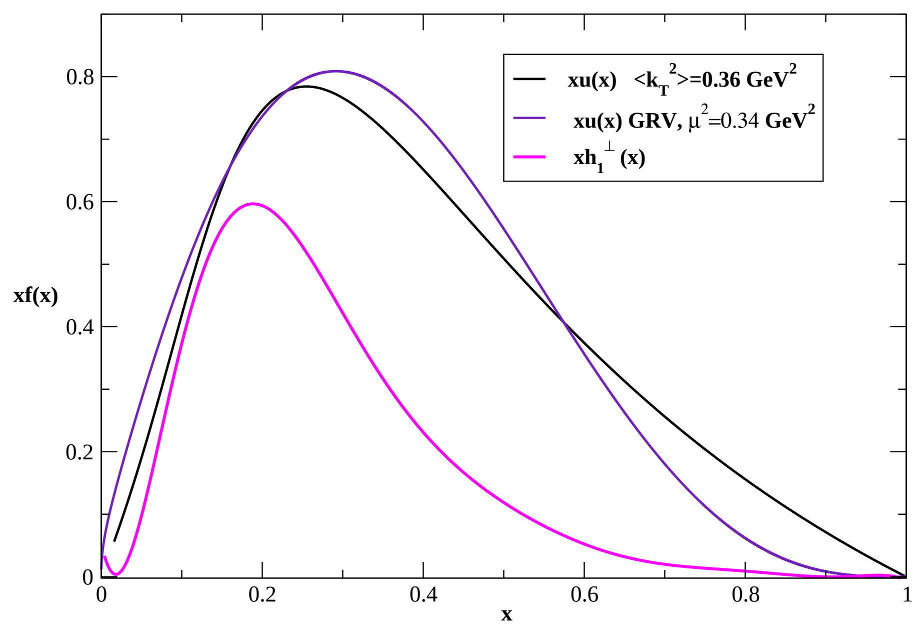
$\Gamma(0,z) \equiv$ incomplete gamma function:

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

Unpolarized Structure Function

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

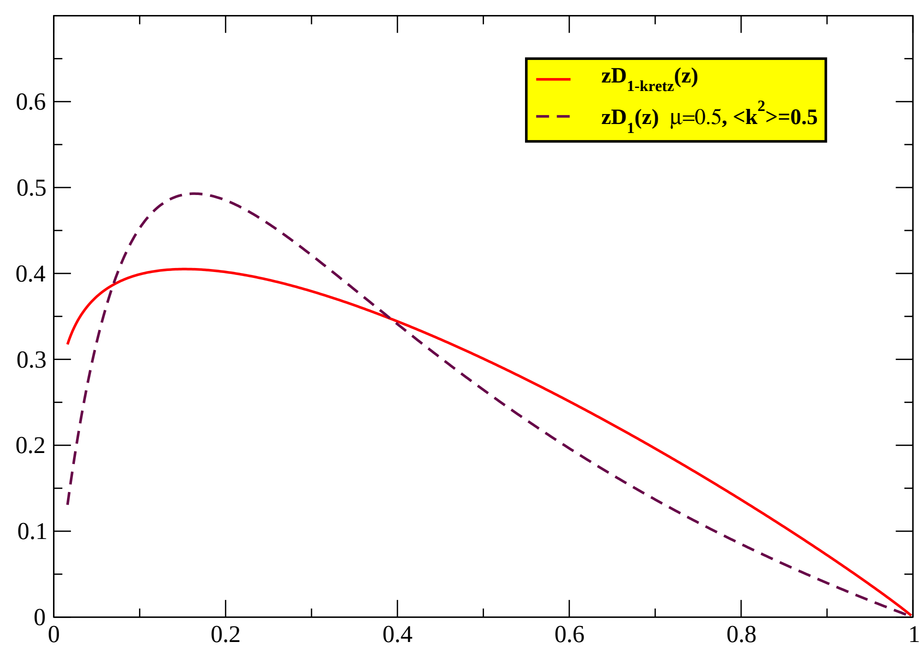
- ⋆ Normalization, $\int_0^1 u(x) = 2$
- Black curve- $xu(x)$
- Purple curve - $xu(x)$ from GRV
- Pink curve $xh_1^{\perp(1/2)(u)}$



Pion Fragmentation Function

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

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



Rescattering Mechanism for T-Odd Collins Function

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

- Gauge-link contribution to the Collins Function:

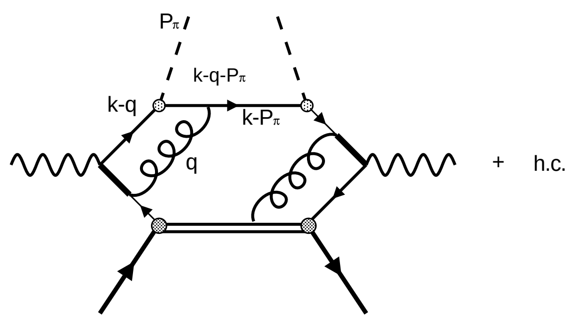


Figure depicts $h_1^\perp \star H_1^\perp \cos 2\phi$ asymmetry. The momenta flow to the quark-pion vertex is shown.

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

$$H_1^\perp(z,k_\perp) \quad = \quad \frac{{N'}^2 f^2 g^2}{(2\pi)^4}\frac{1}{4z}\frac{(1-z)}{z}\frac{\mu}{\Lambda'(k_\perp^2)}\frac{M_\pi}{k_\perp^2}\mathcal{R}(z,\boldsymbol{k}_\perp^2)$$

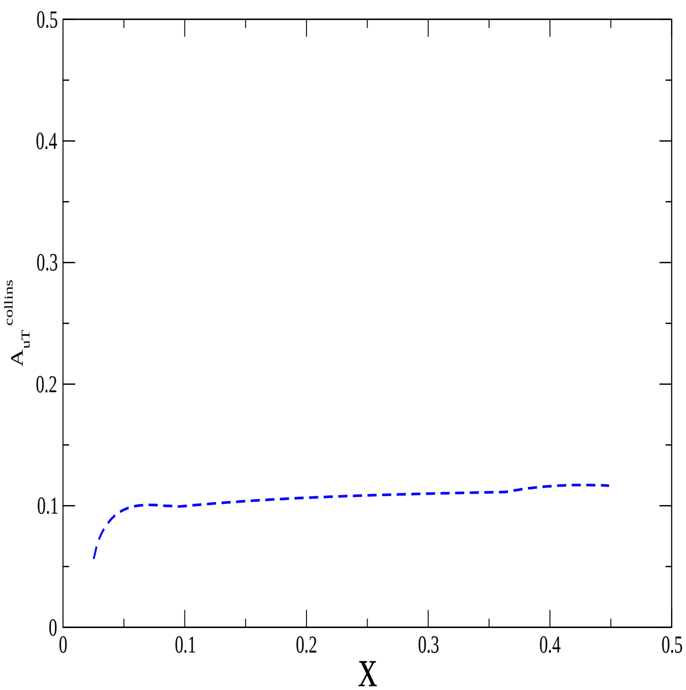
where, $\Lambda'(k_\perp^2) = k_\perp^2 + \frac{1-z}{z^2}M_\pi^2 + \frac{\mu^2}{z} - \frac{1-z}{z}m^2$

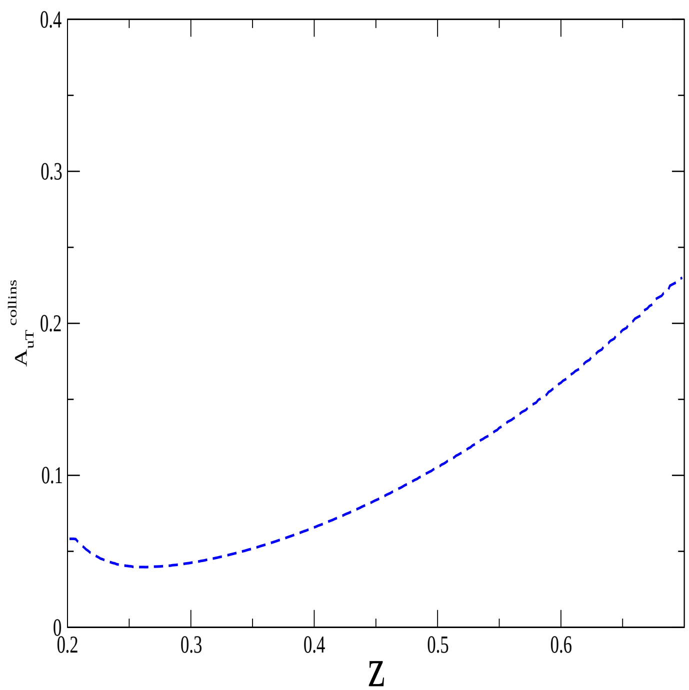
Collins Asymmetry

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

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

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

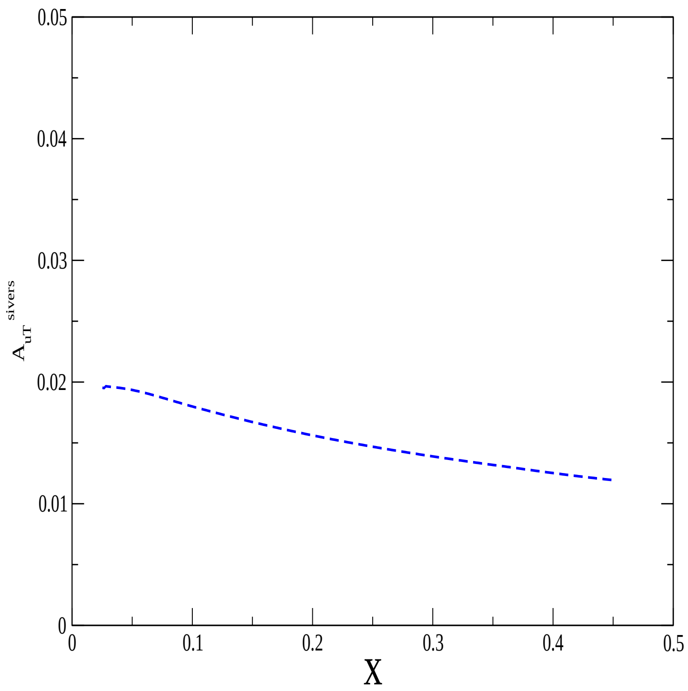


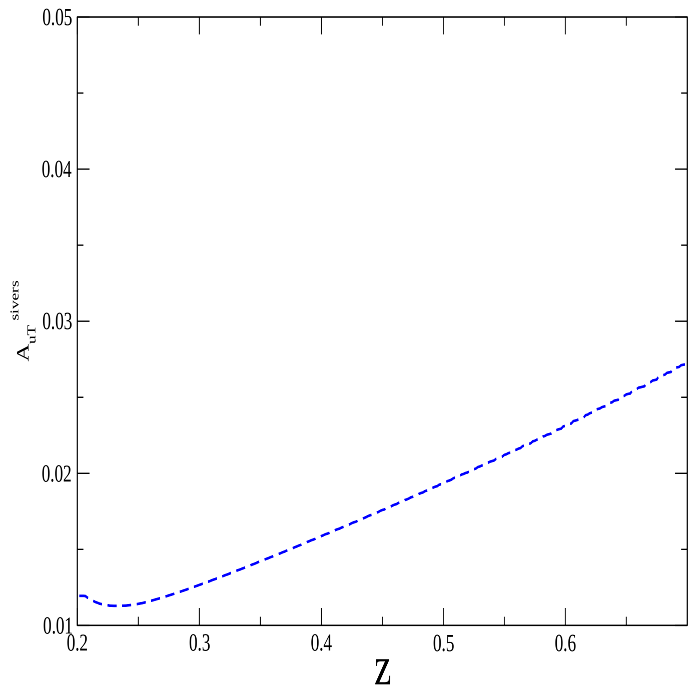


Estimates for Sivers Asymmetry

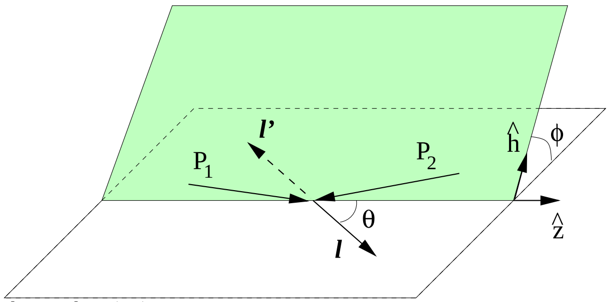
$$\langle \frac{|P_{h\perp}|}{M} \sin(\phi - \phi_S) \rangle_{UT} = \frac{\int d^2 P_{h\perp} \frac{|P_{h\perp}|}{M} \sin(\phi - \phi_S)\, d\sigma}{\int d^2 P_{h\perp}\, d\sigma}$$

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





Unpolarized DRELL YAN $\cos 2\phi$



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

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

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, Boer, Brodsky, Hwang PRD: 2003 Collins Soper PRD: 1977 subleading twist

- Leading twist $\cos 2\phi$ azimuthal asymmetry depends on T-odd distribution $h_1^\perp$.

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

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

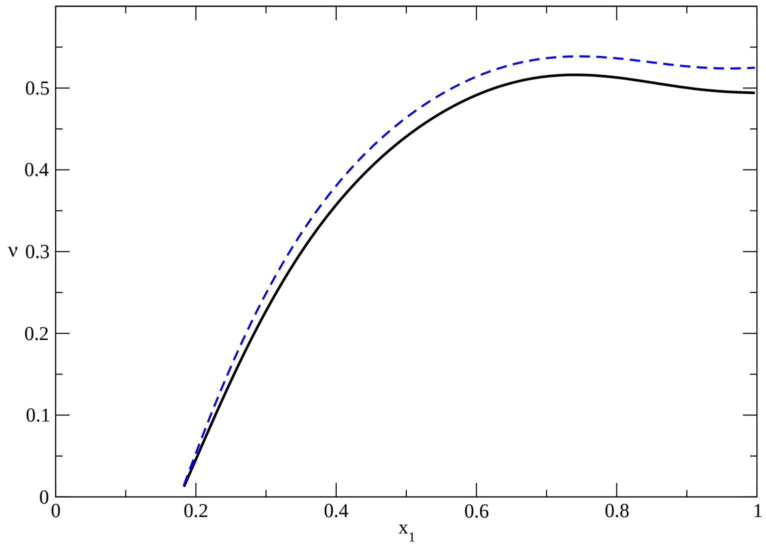
$$\nu = \frac{2\sum_a e_a^2 \mathcal{F}\left[(2\boldsymbol{p}_\perp \cdot \boldsymbol{k}_\perp - \boldsymbol{p}_\perp \cdot \boldsymbol{k}_\perp)\frac{h_1^\perp(x,\boldsymbol{k}_T^2)\bar{h}_1^\perp(\bar{x},\boldsymbol{p}_T)}{M_1 M_2}\right] + \nu_4[w_4 f_1 \bar{f}_1])}{\sum_{a,\bar{a}} e_a^2 \mathcal{F}[f_1 \bar{f}_1]}$$

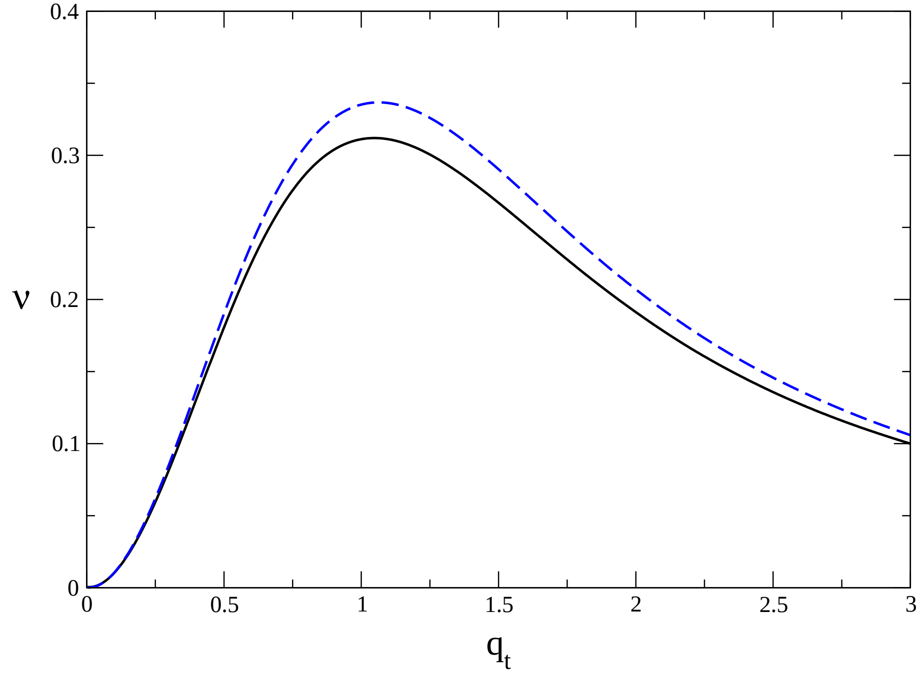
where

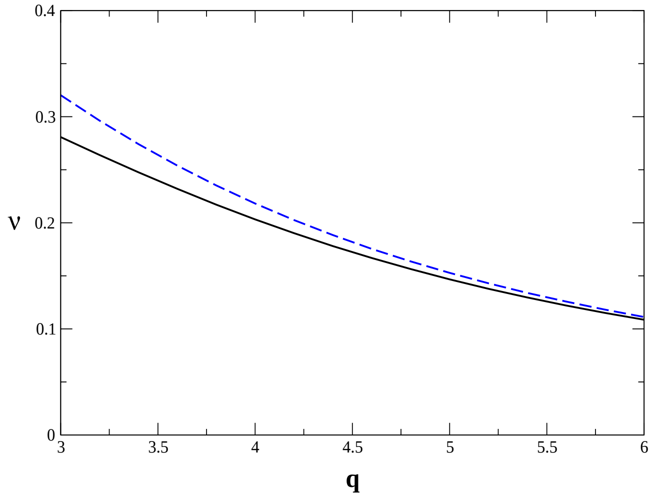
$$\nu_4 = \frac{\frac{1}{Q^2}\sum_a e_a^2 \mathcal{F}\left[w_4\, f_1(x,\boldsymbol{k}_\perp)\bar{f}_1(\bar{x},\boldsymbol{p}_\perp)\right]}{\sum_a e_a^2 \mathcal{F}\left(f_1(x,\boldsymbol{k}_\perp)\bar{f}_1(\bar{x},\boldsymbol{p}_\perp)\right)},$$

where the weight $w_4 = 2\left(\hat{\boldsymbol{h}} \cdot (\boldsymbol{k}_\perp - \boldsymbol{p}_\perp)\right)^2 - (\boldsymbol{k}_\perp - \boldsymbol{p}_\perp)^2$

- Gamberg Goldstein higher twist... In prep
- $s = 50GeV^2$, $x = 0.2 - 1.0$, and $q = 3.0 - 6.0\ GeV$ and $\boldsymbol{q}_T = 0 - 3.0\, GeV$

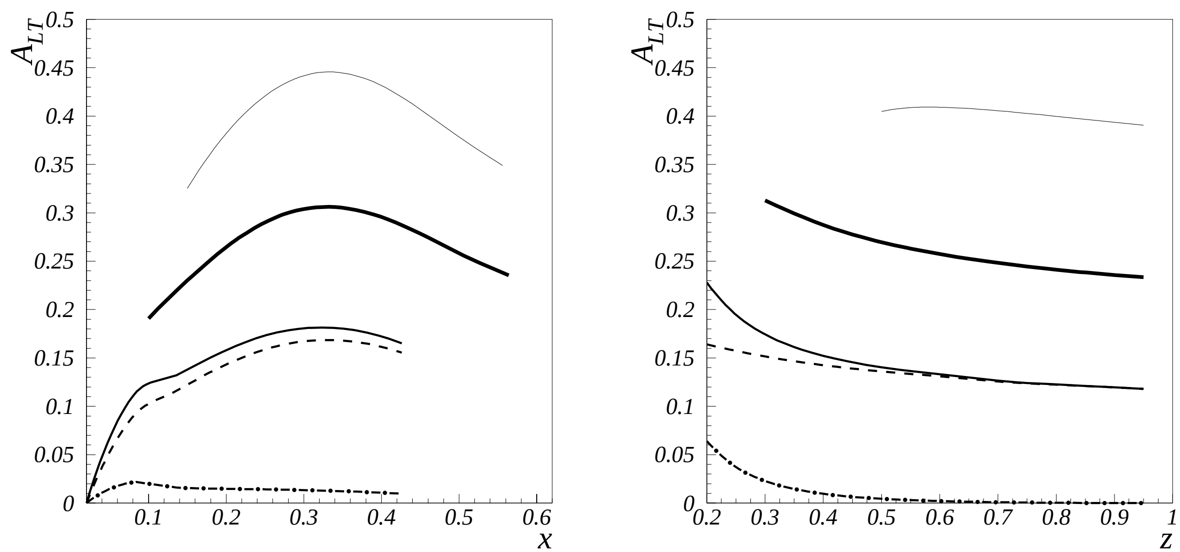

ν
x1
0
0.1
0.2
0.3
0.4
0.5
0.2
0.4
0.6
0.8
1


ν
qt
0
0.1
0.2
0.3
0.4
0.5
1
1.5
2
2.5
3


ν
q
0
0.1
0.2
0.3
0.4
3
3.5
4
4.5
5
5.5
6

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

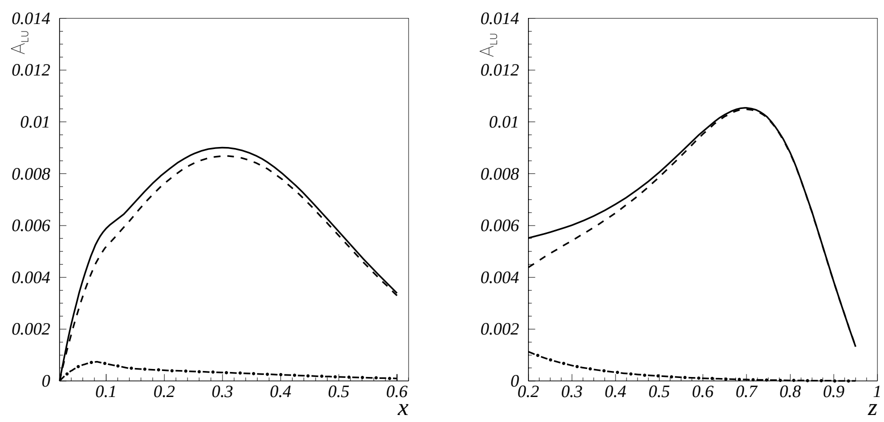
$$A_{LT} = \frac{\lambda_e |\boldsymbol{S}_T| \sqrt{1-y}\, \frac{4}{Q} \left[M\, x\, g_T(x) D_1(z) + M_h\, h_1(x) \frac{E(z)}{z} \right]}{\frac{[1+(1-y)^2]}{y} f_1(x) D_1(z)}$$



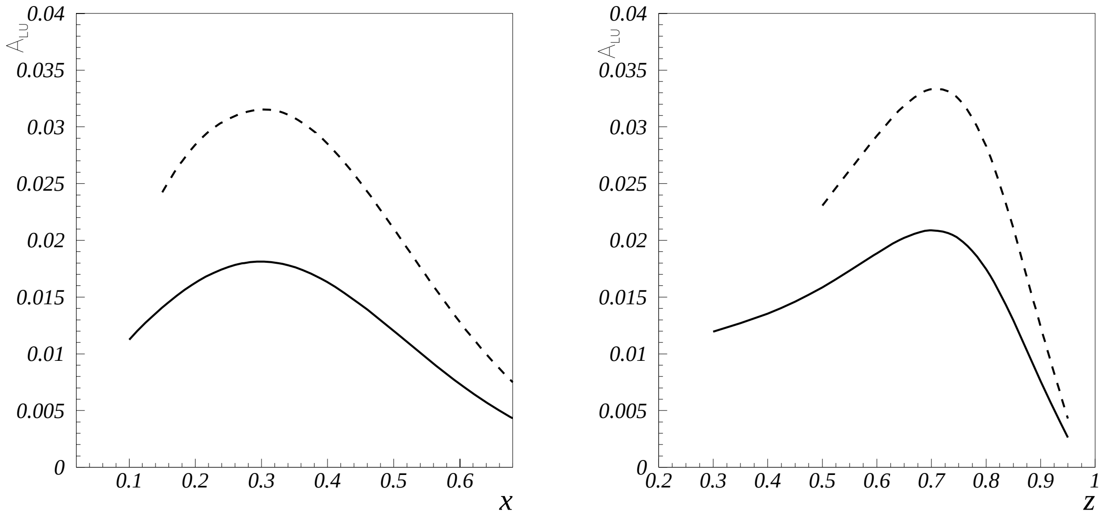
A_{LT} for π^+ production function of x and z at 27.5 GeV energy. The dashed and dot-dashed curves correspond contributions of the two terms of above respectively, and the full curve is the sum. The thin curve corresponds to 6 GeV and the thick curve to 12 GeV energies respectively.

⋆ 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

- 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 stanpoint 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 $\boldsymbol{k}_\perp$ 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