Azimuthal and Transverse Single Spin Asymmetries in SIDIS

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- Remarks on SSA and AA role of p_T in QCD
- Role of Intrinsic $k_\perp$ and Transversity properties of quarks and hadrons in SSAs and AAs
- ⋆ 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
- ⋆ Beam Asymmetry
- Conclusions

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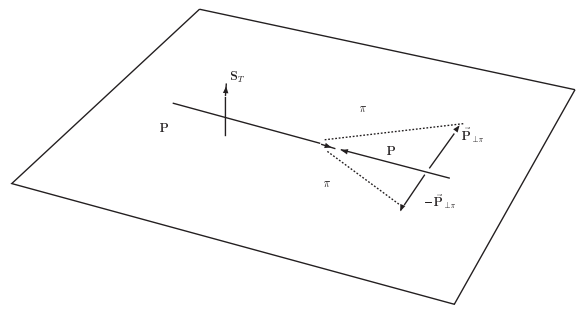
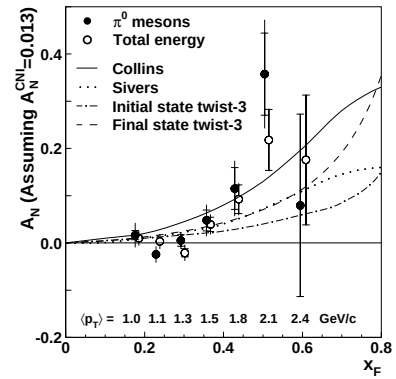
Transverse SSA (TSSA) and AZIMUTHAL ASYMMETRIES (AA)

- LARGE TSSAS OBSERVED

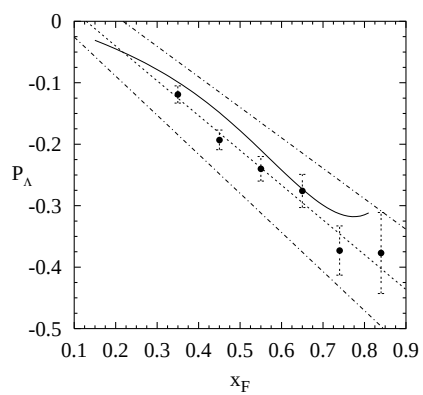
$$A_N = \frac{d\sigma^{p^\uparrow p \to \pi\ X} - d\sigma^{p^\downarrow p \to \pi\ X}}{d\sigma^{p^\uparrow p \to \pi\ X} + d\sigma^{p^\downarrow p \to \pi\ X}}$$

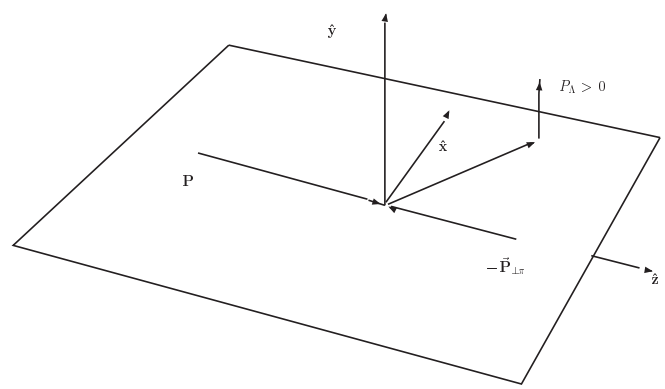




L-R asymmetry of π production and A_N for π_0 production at STAR : PRL 2004

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





P_Λ in p-p scattering from Fermi Lab: 1983: Up-down asymmetry depicted for Λ production in p-p COM-frame.

Transverse SSA (TSSA) and AZIMUTHAL ASYMMETRIES (AA)

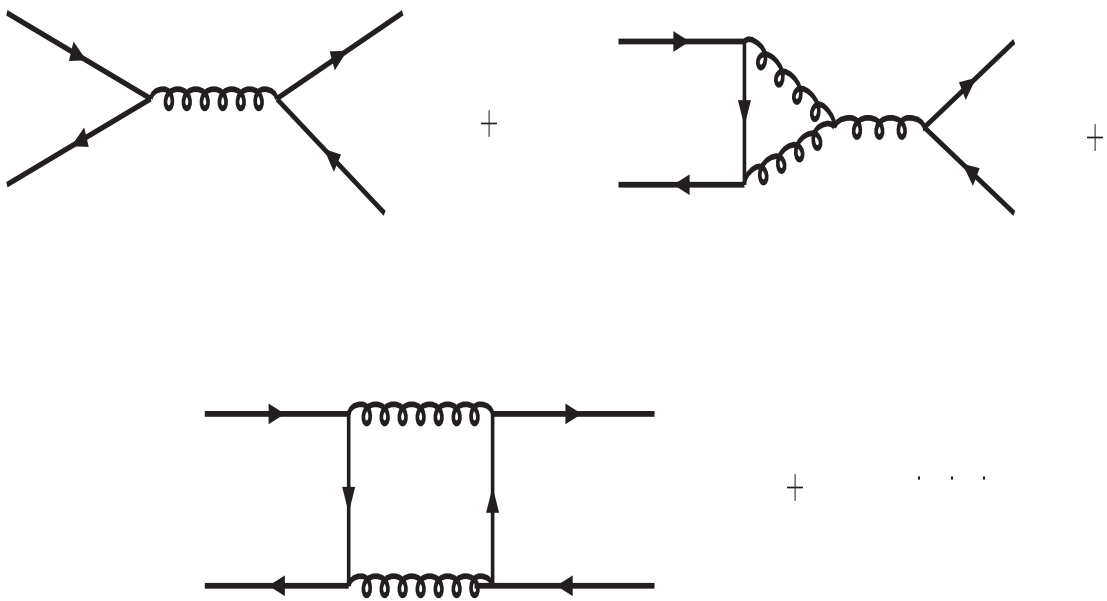
- ⋆ Colinear approx TSSA vanishingly small at large scales and leading order α_s
  Generically,

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

  - ⋆ Requires helicity flip and
  - ⋆ realtive phase btwn helicity amps
  - • At partonic level massless QCD conserves helicity and Born amplitudes are real!
  - ⋆ Interference btwn loops-tree level Kane, Repko, PRL:1978 yield $A_N \sim m_q \alpha_s/\sqrt{s}$

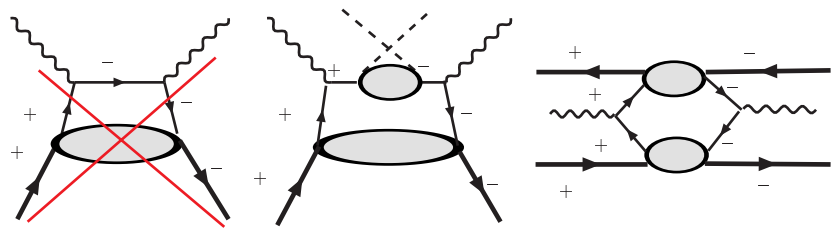
$$P_\Lambda = \frac{d\sigma^{pp\to\Lambda^\uparrow X} - d\sigma^{pp\to\Lambda^\downarrow X}}{d\sigma^{pp\to\Lambda^\uparrow X} + d\sigma^{pp\to\Lambda^\downarrow X}}$$

- $e.g.$ Inclusive Λ production ($pp \to \Lambda^\uparrow X$) PQCD contributions calculated
  Dharmartna & Goldstein PRD 1990
  P_Λ goes like $m_q\alpha_s/\sqrt{s}$ as predicted m_q is the strange quark mass



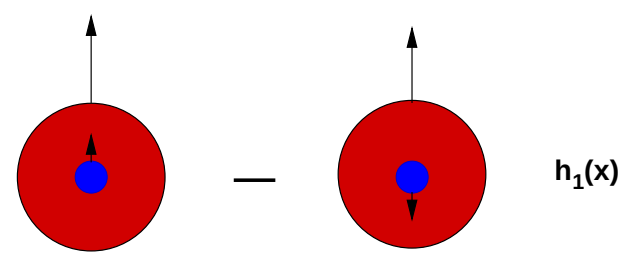
Helicity Flips Accommodated in Hard Scattering, Through "Transversity"

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

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



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

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

Estimate, Gamberg, Hwang, Oganessyan PLB:2004

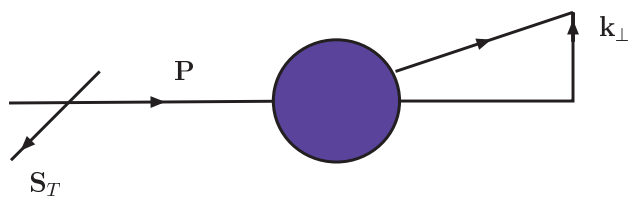
$$A_{LT} = \frac{\lambda_e |\boldsymbol{S}_T| \sqrt{1-y}\, \frac{4}{Q} \left[M\, x\, g_T(x) D_1(z) + M_h\, h_1(x) \frac{E(z)}{z} \right]}{\frac{[1+(1-y)^2]}{y}\, f_1(x) D_1(z)}$$

"T-Odd" (or A_τ) Correlations: Beyond Co-linearity

- 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 sensitive to $\boldsymbol{k}_\perp$ 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 a correlation to account a left-right transverse SSA
  Sivers: PRD 1990 in inclusive π production



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

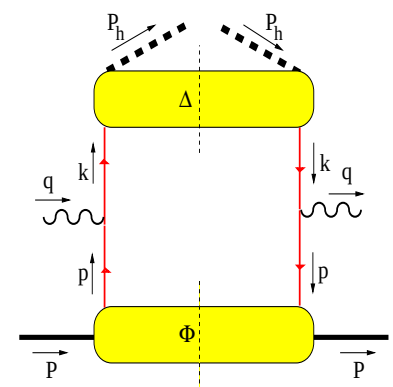
- Initial-Final state effect: $\mathsf{s}_T \cdot (\boldsymbol{p} \times \boldsymbol{P}_{h\perp})$, where s_T is the spin of fragmenting quark, $\boldsymbol{p}$ is quark momentum and $\boldsymbol{P}_{h\perp}$ is transverse momentum produced pion

T-Odd Correlations: Beyond Co-linearity

Recent Times Boer & Mulders and Co. incoporated $\boldsymbol{k}_\perp$ T-odd PDFs and FFs: relevant to hard scattering QCD at leading twist. Adopted Factorized Description

Ellis, Furmanski, Petronzio NPB: 1982, Collins *et al. PQCD...* : 82 , J. Qui PRD: 1990, Levelt & Mulders, Mulders & Tangerman, NPB: 1994, 1996

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



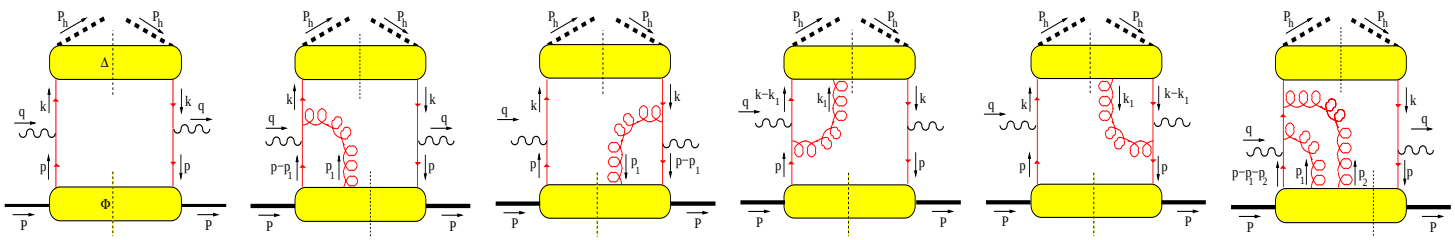
Hadronic Tensor

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

Color Gauge Invariance & T-Odd Contributions to QCD Processes

- Gauge Invariant Distribution and Fragmentation Functions

  Ji, Yuan & Belitsky PLB: 2002, NPB 2003, Boer, Mulder, Pijlman NPB 2003



etc . . .

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

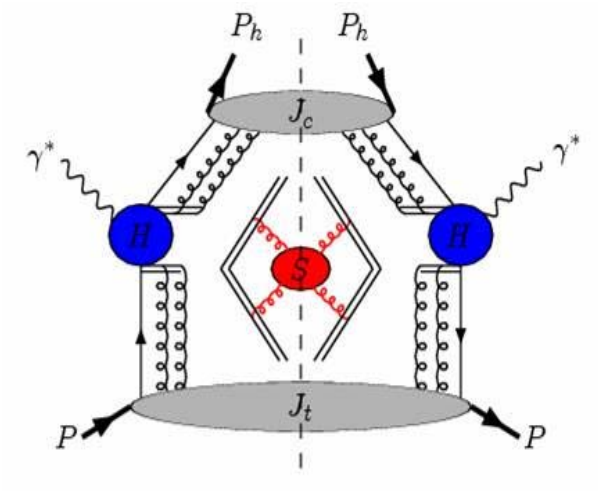
$$\Phi(p,P) = \int \frac{d^3\xi}{2(2\pi)^3} e^{ip\cdot\xi} \langle P|\overline{\psi}(\xi^-,\xi_\perp)\mathcal{G}^\dagger_{[\xi^-,\infty]}|X\rangle\langle X|\mathcal{G}_{[0,\infty]}\psi(0)|P\rangle|_{\xi^+=0}$$

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

$$\mathcal{W}^{\mu\nu}(q,P,P_h) \quad = \quad \frac{1}{2M}\int d^2\boldsymbol{p}_T d^2\boldsymbol{k}_T \delta^2(\boldsymbol{p}_T+\boldsymbol{q}_T-\boldsymbol{k}_T)\mathrm{Tr}\Big[\Phi(x_B,\boldsymbol{p}_T)\gamma^\mu\Delta(z_h,\boldsymbol{k}_T)\gamma^\nu\Big] \;+\; \Big(q\leftrightarrow -q\;,\;\mu\leftrightarrow\nu\Big)$$

More recently building on work of Collins-Soper NPB: 81,

Ji, Ma, Yuan: 2004 & Collins and Metz: 2005



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

$$\Delta(z, \boldsymbol{k}_T) = \frac{1}{4}\{D_1(z, z\boldsymbol{k}_T)\,\not{n}_- + H_1^\perp(z, z\boldsymbol{k}_T)\frac{\sigma^{\alpha\beta}k_{T\alpha}n_{-\beta}}{M_h} + D_{1T}^\perp\,\frac{\epsilon_{\mu\nu\rho\sigma}\gamma^\mu n_-^\nu k_T^\rho S_{hT}^\sigma}{M_h} + \cdots\},$$

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

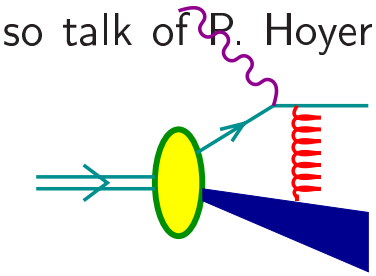
Provides source of T-Odd Contributions to TSSA and Azimuthal Asymmetries in SIDIS

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

And T-Odd Contributions to TSSA and Azimuthal Asymmetries in Drell Yan Boer PRD:1999, see talks of D. Boer and G.R. Goldstein SIR05

Rescattering-ISI/FSI T-Odd Contributions to Asymmetries

PLB: 2002 Brodsky, Hwang, and Schmidt demonstrate rescattering of a gluon could produce the necessary phase leading to nonzero SSAs at *Leading Twist* see also talk of P. Hoyer and PRD: 2002 and ...



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

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

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

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

SIDIS and Transversity Properties at 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:

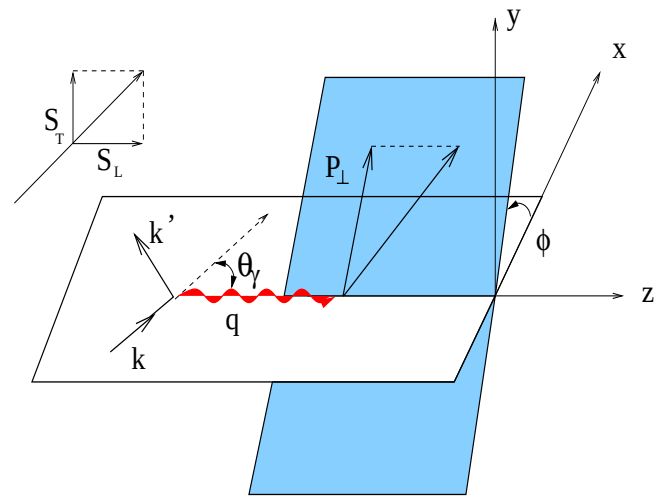
  $P_{h\perp}$ - hadron transverse momentum

  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.



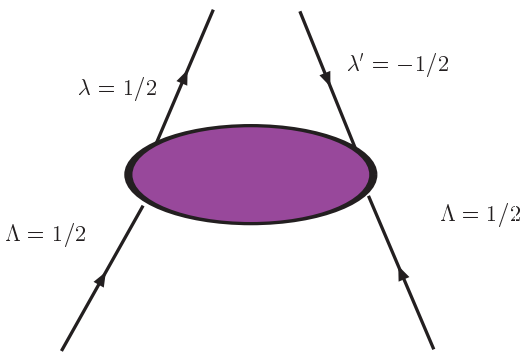
$$\langle \frac{P_{h\perp}}{M_\pi} \sin(\phi + \phi_s) \rangle_{UT} = \frac{\int d\phi_s \int d^2 P_{h\perp} \frac{P_{h\perp}}{M_\pi} \sin(\phi + \phi_s) \left(d\sigma^\uparrow - d\sigma^\downarrow\right)}{\int d\phi_s \int d^2 P_{h\perp} \left(d\sigma^\uparrow + d\sigma^\downarrow\right)}$$

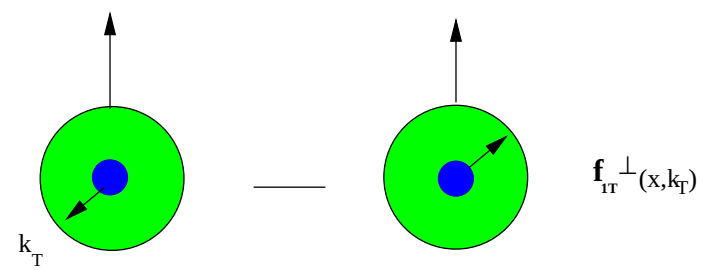
$$= |S_T| \frac{2(1-y) \sum_q e_q^2 h_1(x) z H_1^{\perp(1)}(z)}{\left(1 + (1-y)^2\right) \sum_q e_q^2 f_1(x) D_1(z)}$$

Sivers Asymmetry in SIDIS

- Probes the probability that for a transversely polarized target, pions are produced asymmetrically about the transverse spin vector:
  (Sivers PRD: 1990, Anselmino & Murgia PLB: 1995 ...)

  Hadron helicity flip furnished by orbital angular momentum, quarks have $\boldsymbol{k}_\perp$



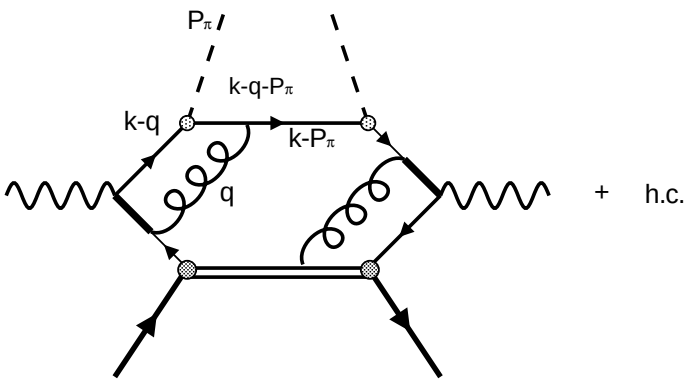


$$\langle \frac{|P_{h\perp}|}{M} \sin(\phi - \phi_S) \rangle_{UT} \quad = \quad |\boldsymbol{S}_T| \frac{(1 + (1-y)^2) \sum_q e_q^2 f_{1T}^{\perp(1)}(x) z D_1^q(z)}{(1 + (1-y)^2) \sum_q e_q^2 f_1(x) D_1(z)},$$

Reaction Mechanism explained as FSI

⋆ See Star and HERMES Data

$\cos 2\phi$ Asymmetry



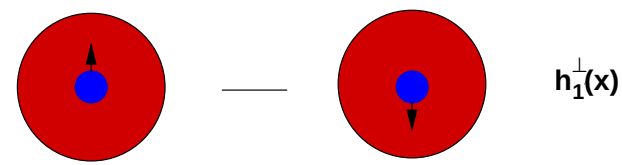
$$A_{UU}^{\cos(2\phi)} \propto \frac{\sum_q e_q^2 h_1^{\perp(1)}(x,Q^2) z^2 \cdot H_1^{\perp(1)q}(z,Q^2)}{\sum_q e_q^2 f_1^q(x,Q^2) \cdot D_1^q(z,Q^2)}$$

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

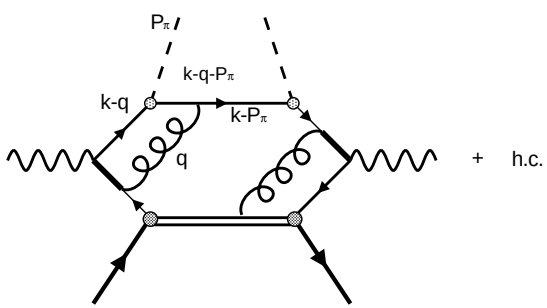
Rescattering Mechanism to Generate T-Odd Function $h_1^\perp$

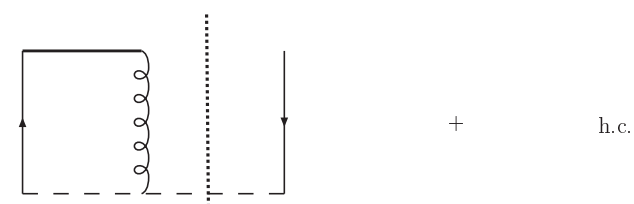
Goldstein, Gamberg–ICHEP-proc., Amsterdam: 2002, hep-ph/0209085, Gamberg, Goldstein, Oganessyan PRD 2003

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



$$\Phi^{[\sigma^{\perp +}\gamma_5]}_{[h_1^\perp]} = \frac{\varepsilon_{+-\perp j}\, k_{\perp j}}{M} h_1^\perp(x, k_\perp)$$





$$\Phi^{[\Gamma]}(x, k_\perp) = \sum_X \int \frac{d\xi^- d^2\xi_\perp}{2(2\pi)^3} e^{-i(\xi\cdot\vec{k}_\perp)} \langle P|\overline{\psi}(\xi^-, \xi_\perp)|X\rangle\langle X| \left(-ie_1 \int_0^\infty A^+(\xi^-, 0) d\xi^-\right) \Gamma\psi(0, 0_\perp)|P\rangle|_{\xi^+=0} \quad + \quad \text{h.c.}$$

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

Estimates of T-odd Contribution in SIDIS and Azimuthal Asymmetries Drell Yan (GSI program)

$\cos 2\phi$ Asymmetry

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

  Goldstein, L. Gamberg, ICHEP 2002;

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

$$\begin{aligned} h_1^{\perp}(x, k_\perp) &= f_{1T}^{\perp}(x, k_\perp) \\ &= \frac{g^2 e_1 e_2}{4\pi(2\pi)^3} \frac{(1-x)(m+xM)}{\Lambda(k_\perp^2)} \frac{M}{k_\perp^2} \ln \frac{\Lambda(k_\perp^2)}{\Lambda(0)} \end{aligned}$$

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

- 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

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

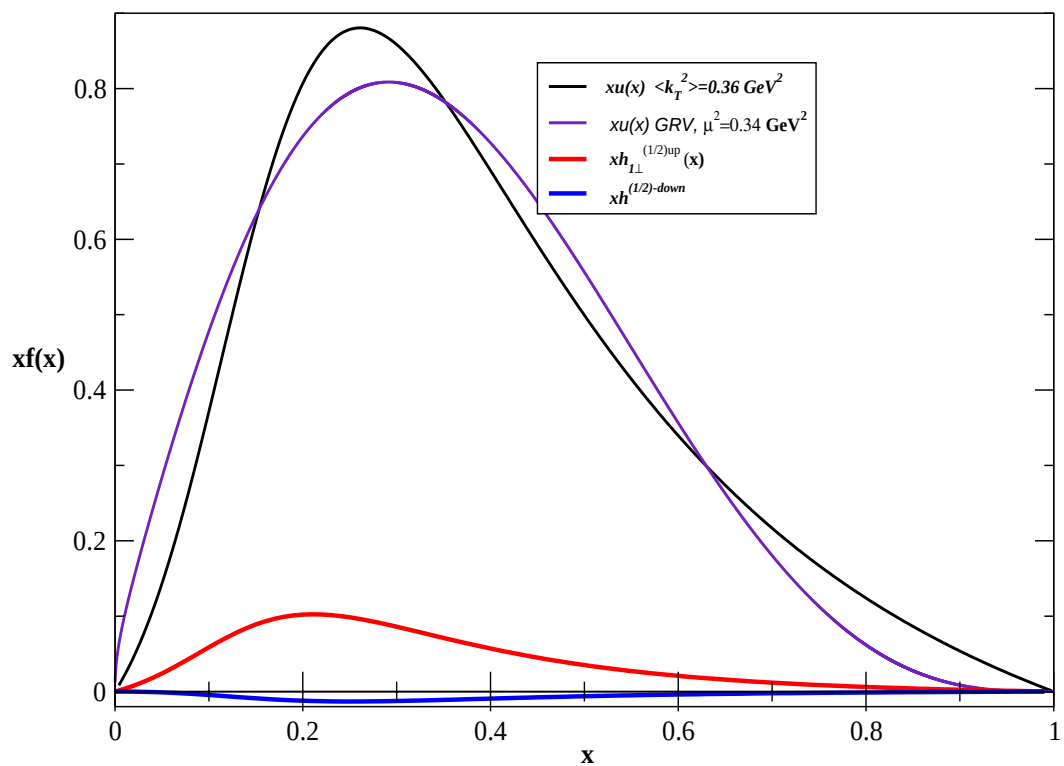
$\Gamma(0,z) \equiv$ incomplete gamma function:

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

Boer-Mulders and Unpolarized Structure Function

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

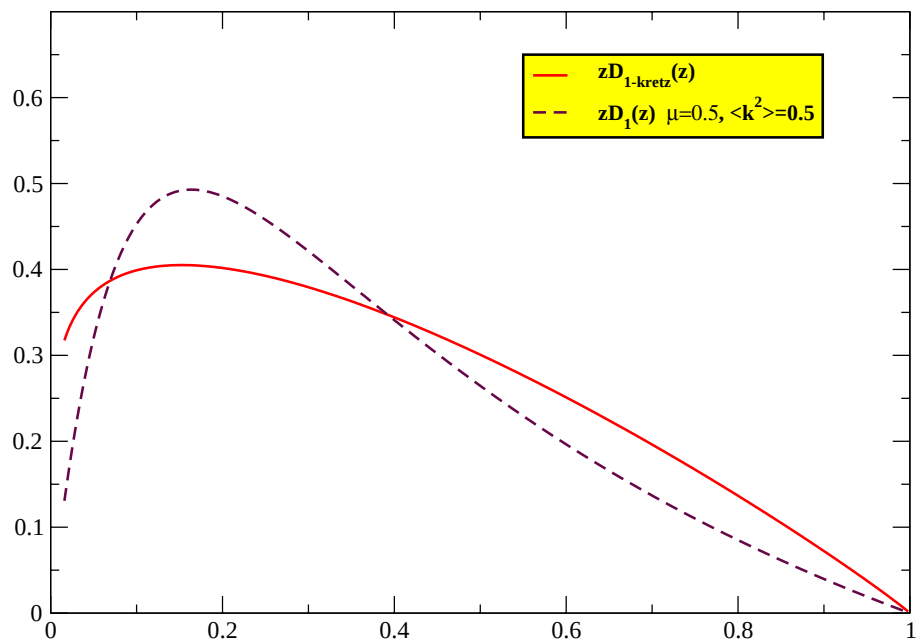
- ⋆ Normalization, $\int_0^1 u(x) = 2$
- Black curve- $xu(x)$
- Purple curve - $xu(x)$ from GRV
- Red curve $xh_1^{\perp(1/2)(u)}$



Pion Fragmentation Function

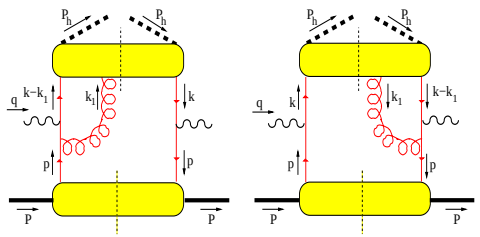
$$D_1(z) = \frac{N'^2 f_{qq\pi}^2}{4(2\pi)^2}\frac{1}{z}\frac{(1-z)}{z}\Big\{\frac{m^2-\Lambda'(0)}{\Lambda'(0)} - \Big[2b'\Big(m^2-\Lambda'(0)\Big)-1\Big]e^{2b'\Lambda'(0)}\Gamma(0,2b'\Lambda'(0))\Big\},$$

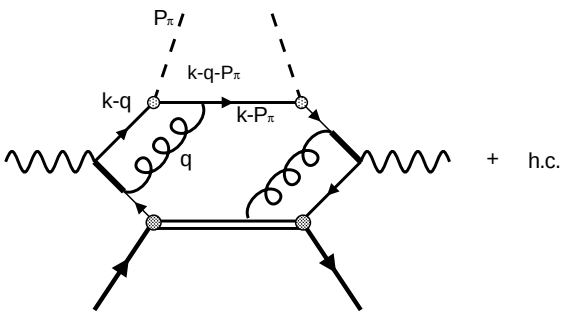
which, multiplied by z at $< k_\perp^2 >= (0.5)^2$ GeV^2 and $\mu = m$, estimates the distribution of Kretzer, PRD: 2000

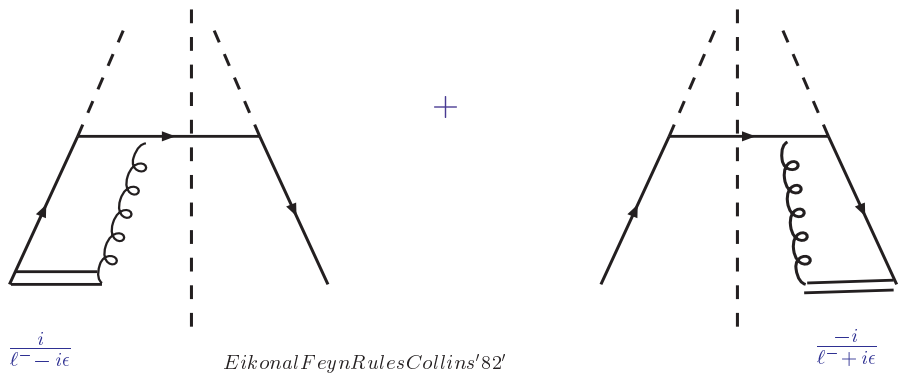


Gauge Link-Pole Contribution to T-Odd Collins Function

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







in agreement with BPM 2003 "pole contribution" We evaluate the projection $\Delta^{[i\sigma^{\perp -}\gamma_5]}$, which results in the leading twist, contribution to T-odd pion fragmentation

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

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

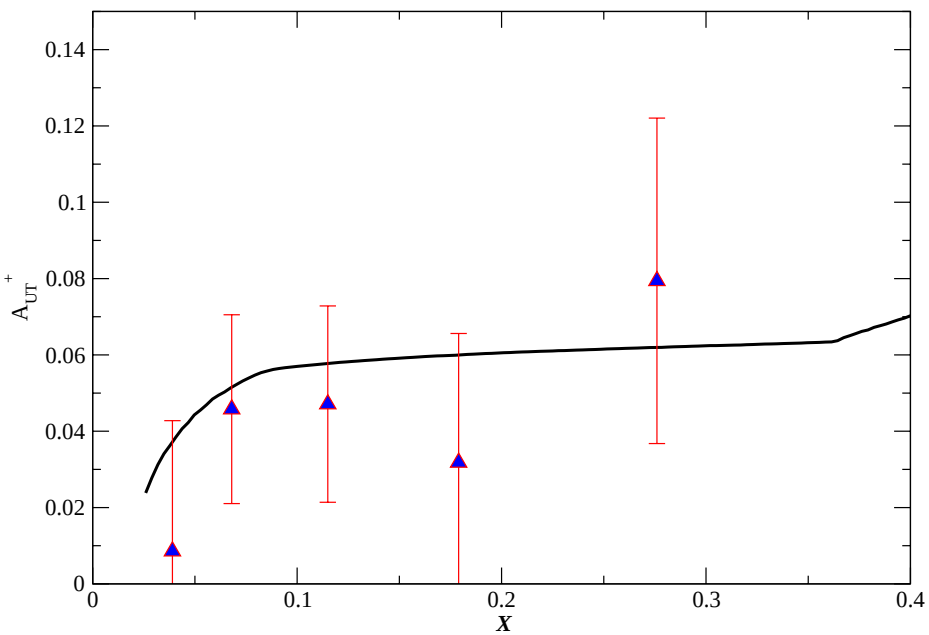
Collins Asymmetry

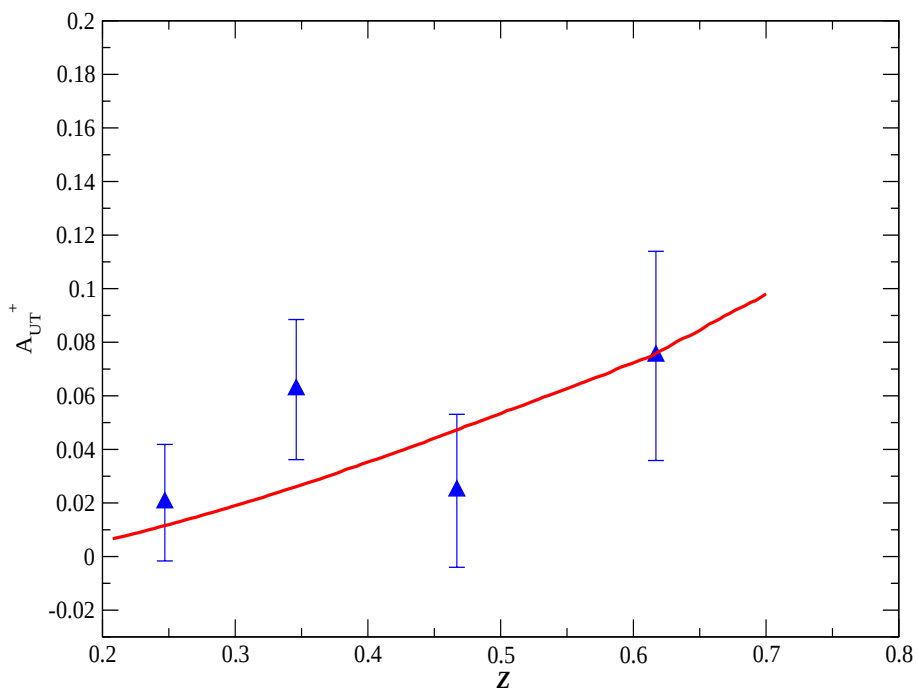
Gamberg, Goldstein, Oganessyan PRD 2003: updated For the HERMES kinematics

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

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

Data from A. Airapetian et al. PRL94,2005



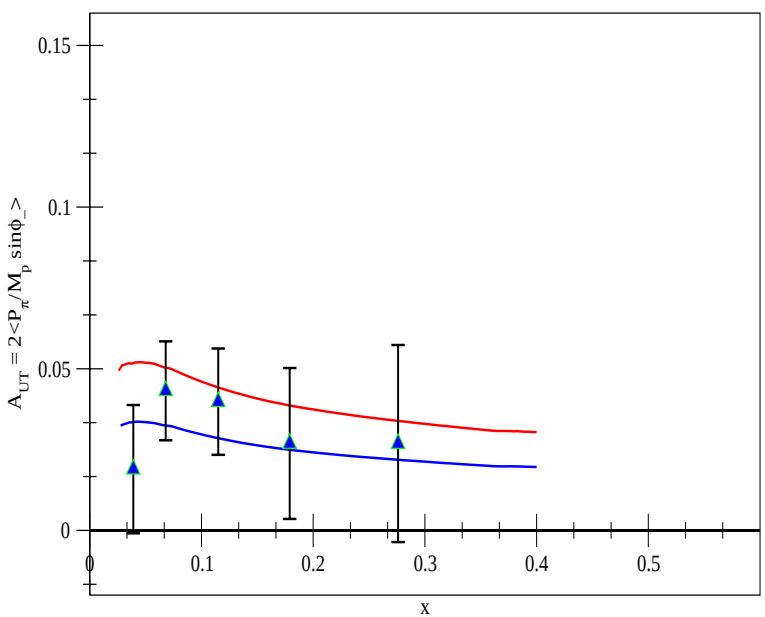


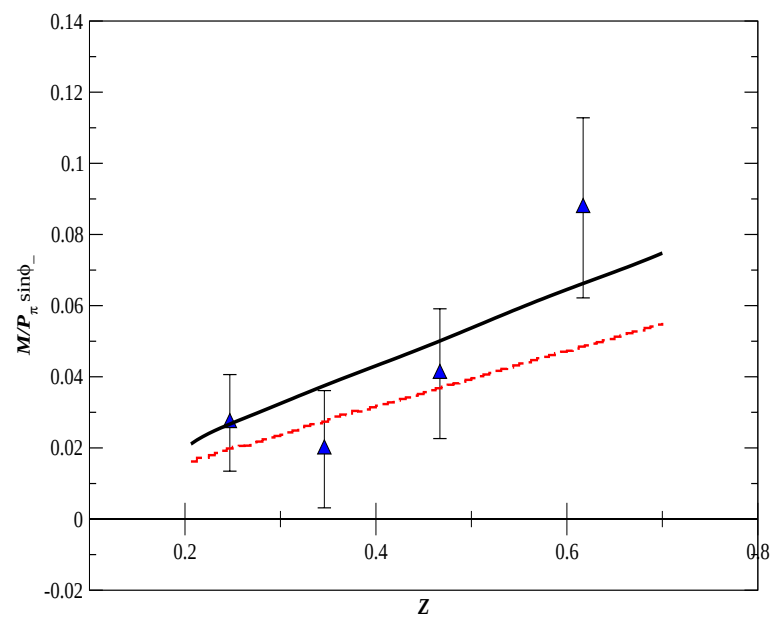
Estimates for Sivers Asymmetry

Data from A. Airapetian et al. PRL94,2005

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

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

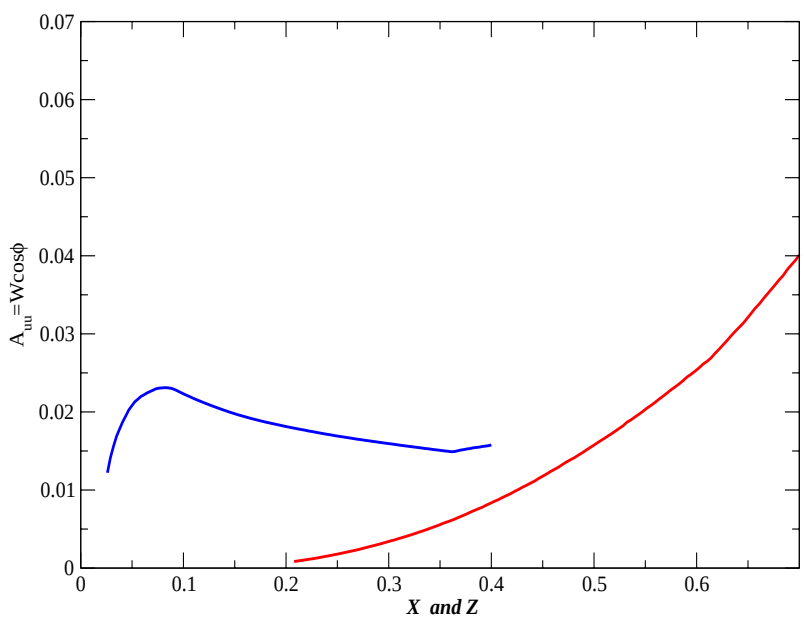




Double T-odd $\cos 2\phi$ asymmetry

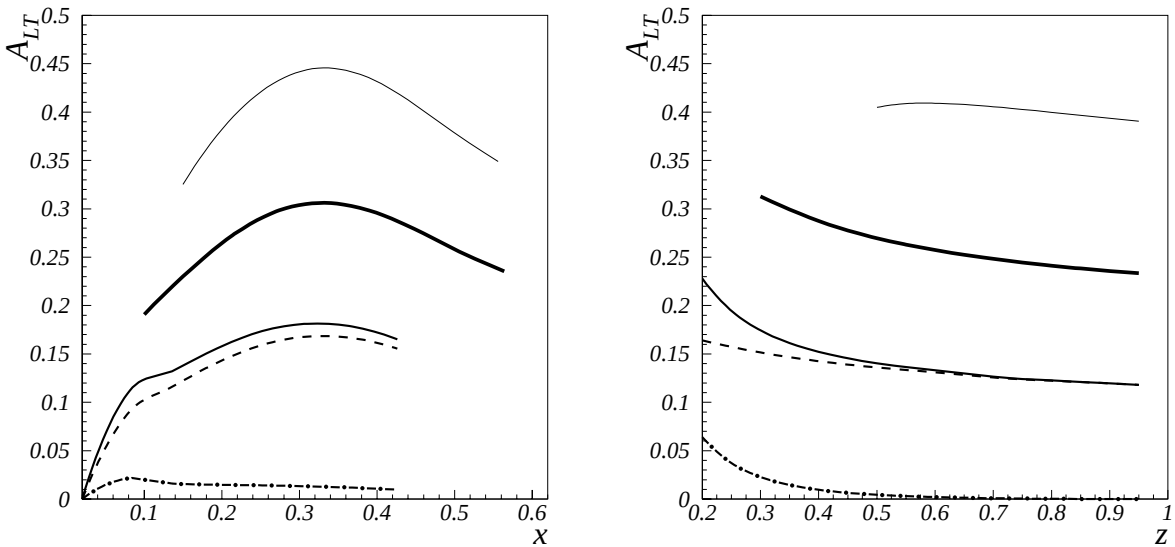
Transversity of quarks inside an unpolarized hadron, and $\cos 2\phi$ asymmetries in unpolarized semi-inclusive DIS

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



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

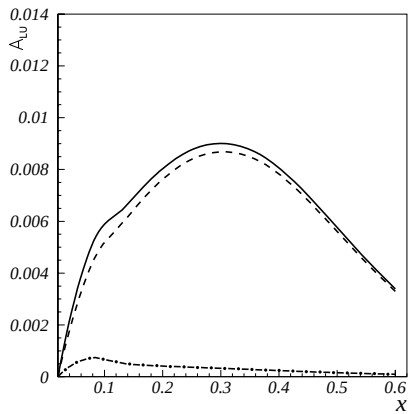
$$A_{LT} = \frac{\lambda_e |\boldsymbol{S}_T| \sqrt{1-y}\, \frac{4}{Q} \left[M\, x\, g_T(x) D_1(z) + M_h\, h_1(x) \frac{E(z)}{z} \right]}{\frac{[1+(1-y)^2]}{y}\, f_1(x) D_1(z)}$$

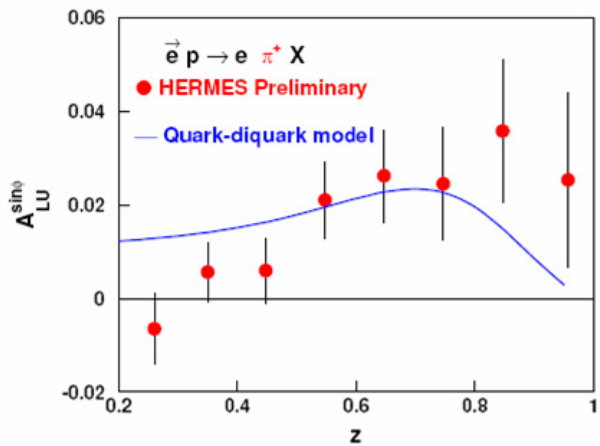


A_{LT} for π^+ production function of x and z at 27.5 GeV energy. The dashed and dot-dashed curves correspond contributions of the two terms of above respectively, and the full curve is the sum. The thin curve corresponds to 6 GeV and the thick curve to 12 GeV energies respectively.

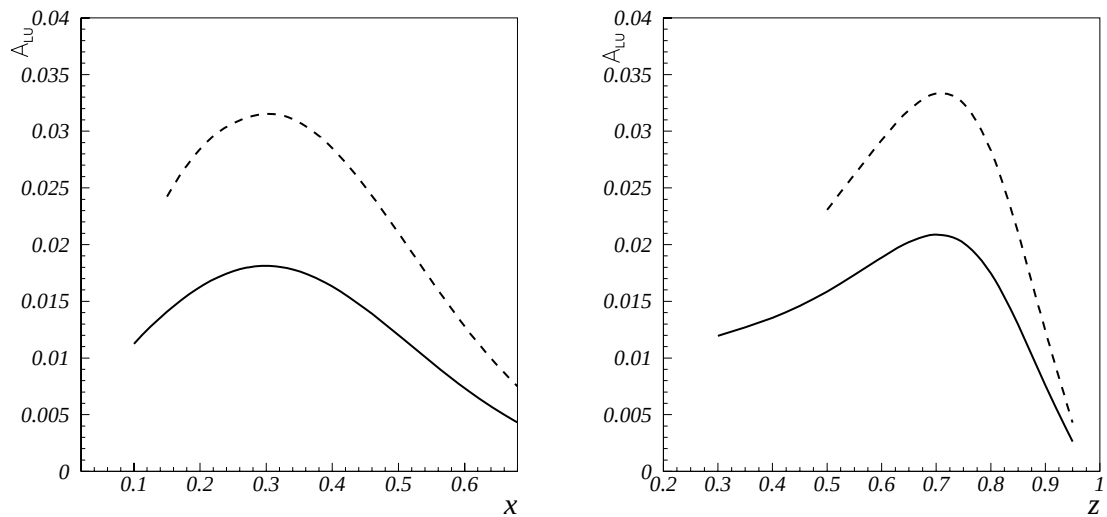
★ Bean Asymmetry Estimate of this effect, Gamberg, Hwang, Oganessyan PLB:2004

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





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

- 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 $\langle k_\perp \rangle$

$\star$ 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