"Transversity" Correlations in Azimuthal and Single Spin Asymmetries

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Transversity 2005 *Villa Olma*, Como, Italy

- Remarks on TSSA: QCD Correlations btwn. intrinsic $k_\perp$ and transverse spin S_T properties of hadrons and quarks
- ⋆ "Novel" Transversity Properties in Hard Scattering
- ⋆ Reaction Mechanism-ISI/FSI: "T-odd" Structure and Fragmentation Functions and role in TSSA and AA
- ⋆ Estimates of the Collins and Sivers Asymmetries
- ⋆ Double T-odd $\cos 2\phi$ asymmetry: SIDIS (DRELL-YAN-talk of G. Goldstein)
- ⋆ Status: Investigation of Collins Function Spec. Model
- ⋆ Other Method to Access Transversity
- Conclusions

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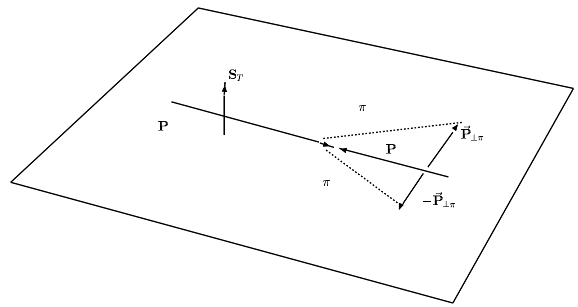
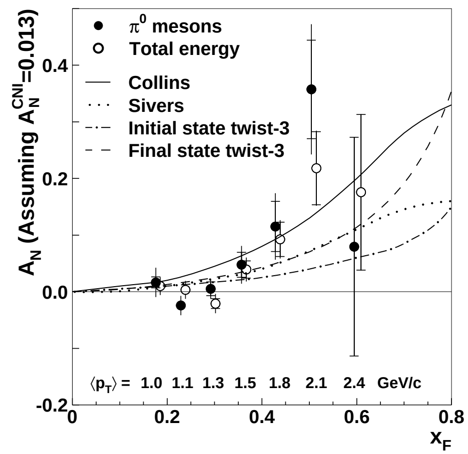
Transverse SSA (TSSA) and AZIMUTHAL ASYMMETRIES (AA)

- LARGE TSSAS OBSERVED

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

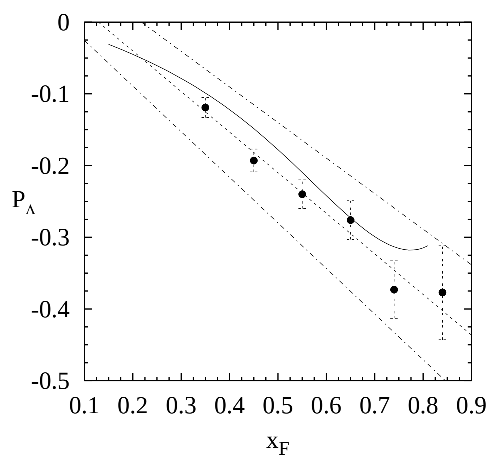


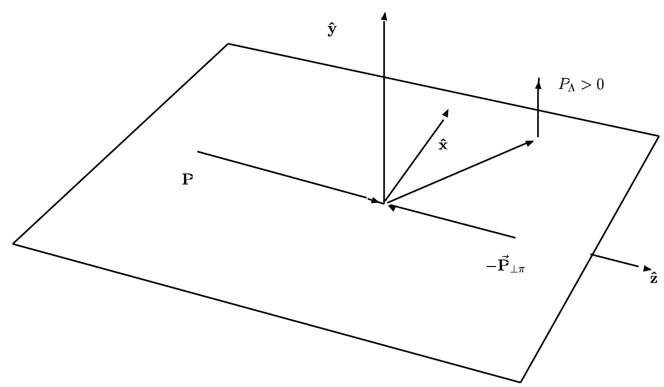


L-R asymmetry of π production and A_N for π_0 production at STAR : PRL 2004

P_Λ in p-p scattering from Fermi Lab

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





Heller,...,Bunce PRL:1983 PRL: 1983: Up-down asymmetry depicted for Λ production in p-p COM-frame.

Transverse SSA (TSSA) and AZIMUTHAL ASYMMETRIES (AA)

⋆ Colinear approximation

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* as well as relative phase btwn helicity amps
- • At partonic level massless QCD conserves helicity Born amplitudes are real!
- ⋆ Interference btwn loops-tree level Kane, Repko, PRL:1978 yield $A_N \sim m_q \alpha_s / \sqrt{s}$
- • Twist three effects analyzed for moderately large p_T
  Efremov-Teryaev:PLB 1985, Qiu Sterman:PRL 1991, and Koike:PLB 2000

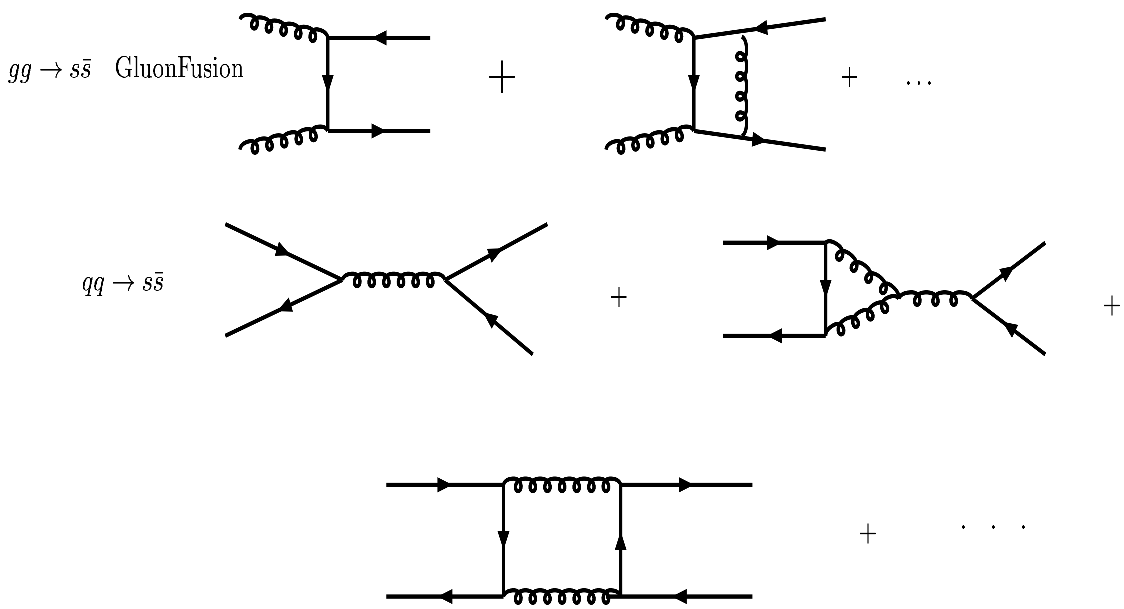
Inclusive Λ production From PQCD ($pp \to \Lambda^{\uparrow} X$)

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

- Need a strange quark to Polarize a Λ ($pp \to \Lambda^{\uparrow} X$) PQCD contributions calculated

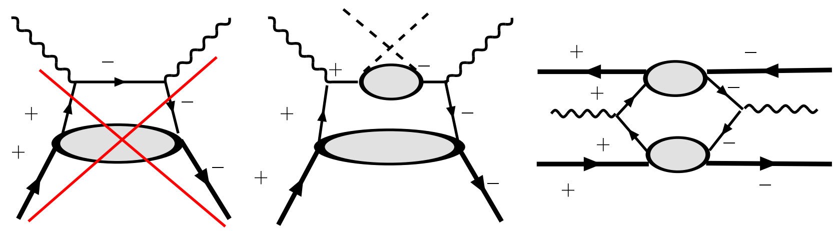
  Dharmartna & Goldstein PRD 1990

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



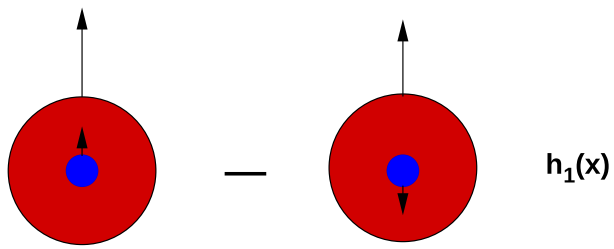
Helicity Flips Accommodated in Hard Scattering, from "Transversity" Distributions

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)



$\star$ 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**

Transversity and Twist-3 Contributions to Asymmetries

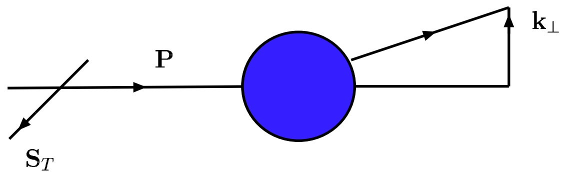
- ⋆ SIDIS:Jaffe and Ji PRL:1993 encountered at twist three level double spin asymmetry
  Estimate, Gamberg, Hwang, Oganessyan PLB:2004

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

- ⋆ Analogous process in Drell-Yan $\pi P \to \mu^+ \mu^- X$
  Ji PLB:1992

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

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



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

- Correlation accounts for left-right transverse SSA Sivers: PRD 1990 in inclusive π production (Anselmino & Murgia PLB: 1995 ...)

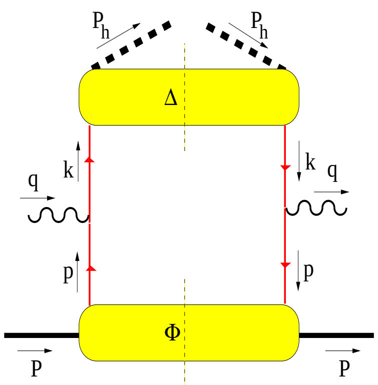
- Collins NPB 1993 proposed T-odd correlation of transversely polarized fragmenting quark: TSSA in lepto-production $\ell\, \vec{p} \to \ell'\, \pi\, X$
  Initial-Final state effect: $s_T \cdot (\boldsymbol{p} \times \boldsymbol{P}_{h\perp})$, s_T is the spin of fragmenting quark, $\boldsymbol{p}$ is quark momentum and $\boldsymbol{P}_{h\perp}$ is transverse momentum produced pion

T-Odd Correlations: Beyond Co-linearity

Recent Times Boer & Mulders and Co. incorporated $\boldsymbol{k}_\perp$ 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

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



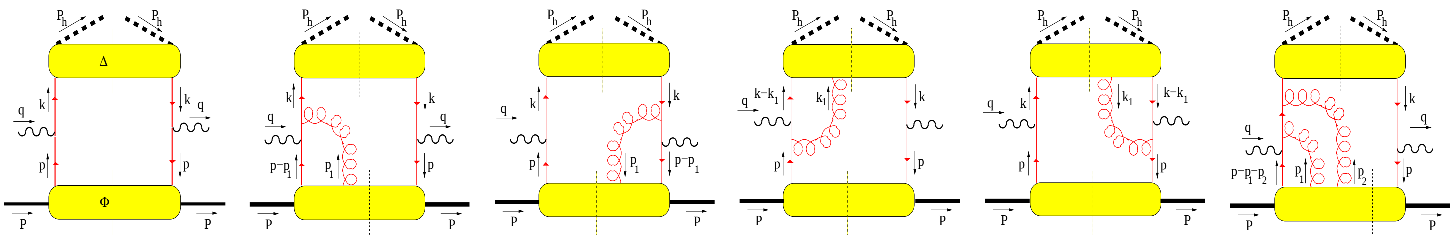
Hadronic Tensor

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

Color Gauge Invariance Built into Factorized QCD at ''leading twist''-Wilson Line & T-Odd Contributions to QCD Processes

- Gauge Invariant Distribution and Fragmentation Functions

  Boer, Mulder: NPB 2000, Ji, Yuan & Belitsky PLB: 2002, NPB 2003, Boer, Mulder, Pijlman NPB 2003



etc . . .

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

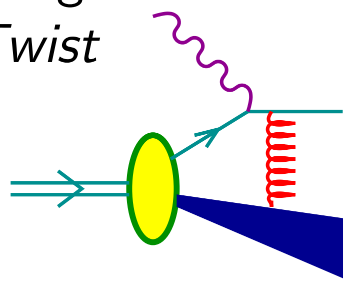
$$\Phi(p,P) = \int \frac{d^3\xi}{2(2\pi)^3} e^{ip\cdot\xi} \langle P|\overline{\psi}(\xi^-,\xi_\perp)\mathcal{G}^\dagger_{[\xi^-,\infty]}|X\rangle\langle X|\mathcal{G}_{[0,\infty]}\psi(0)|P\rangle|_{\xi^+=0}$$

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

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

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*



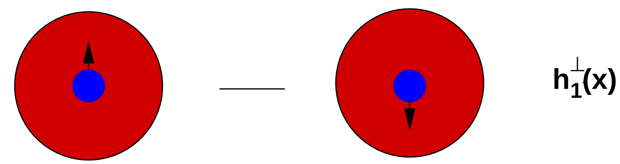
Initial-Final state effect: $\boldsymbol{S}_T \cdot (\boldsymbol{P} \times \boldsymbol{k}_\perp)$

- Ji, Yuan PLB: 2002 describe effect in terms of gauge invariant distribution functions
- 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
  $f_{1T}^{\perp}(x, k_\perp)|_{\rm SDIS} = -f_{1T}^{\perp}(x, k_\perp)|_{\rm DY}$

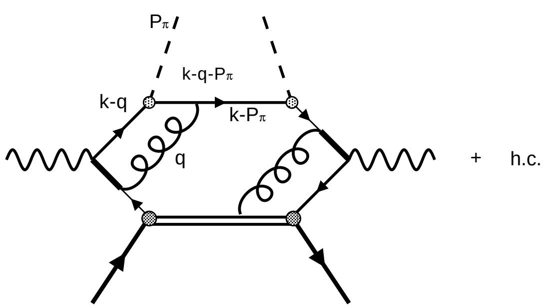
FSI Mechanism can Generate Boer-Mulders- $h_1^\perp$

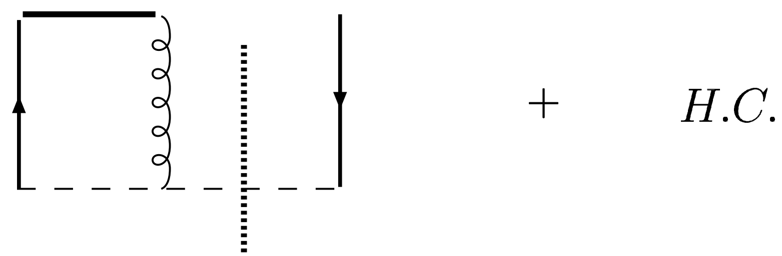
Goldstein, Gamberg–ICHEP-proc., Amsterdam: 2002, hep-ph/0209085, G, G and Oganessyan PRD 2003

- $h_1^\perp$ Naturally defined from gauge invariant TMD: Co-joined with $H_1^\perp$ enters $\cos 2\phi$ AA
- Applied "eikonal Feynman rules"
  to calculate (Collins, Soper, NPB: 1982)



$$\Phi^{[\sigma^{\perp +}\gamma_5]}_{[h_1^\perp]}(x, k_\perp) \quad = \quad \frac{1}{2}\int dp^- \mathrm{Tr}\left(i\sigma^{+\perp}\gamma_5\Phi\right) = \frac{\varepsilon_{+-\perp j}k_{\perp j}}{M}h_1^\perp(x, k_\perp)$$





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

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

Provide source of T-Odd Contributions to TSSA and AA

- **Enter the *leading twist* distribution and fragmentation correlators "T-odd" Distribution Functions: Transversity Properties of quarks in Hadrons**

Boer, Mulder: PRD 1998

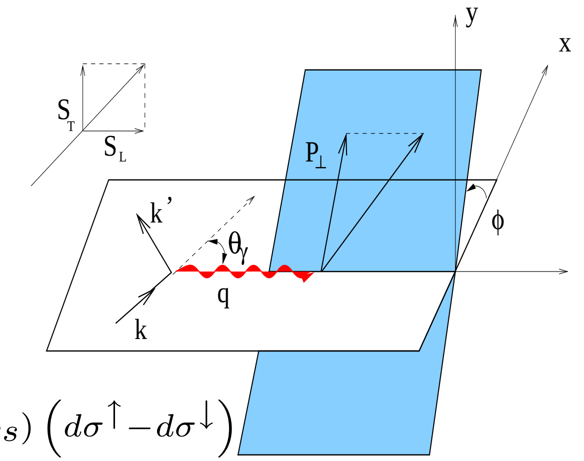
$$\Delta(z, \boldsymbol{k}_\perp) = \frac{1}{4}\{D_1(z, z\boldsymbol{k}_\perp)\, \not{n}_- + H_1^\perp(z, z\boldsymbol{k}_\perp)\frac{\sigma^{\alpha\beta}k_{\perp\alpha}n_{-\beta}}{M_h} + D_{1T}^\perp\frac{\epsilon_{\mu\nu\rho\sigma}\gamma^\mu n_-^\nu k_\perp^\rho S_{hT}^\sigma}{M_h} + \cdots\},$$

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

SIDIS cross section

$$\begin{aligned}
d\sigma^{\ell N\to\ell\pi X}_{\{\lambda,\Lambda\}} \quad &\propto \quad f_1 \otimes d\hat{\sigma}^{\ell q\to\ell q} \otimes D_1 + \frac{k_\perp}{Q} f_1 \otimes d\hat{\sigma}^{\ell q\to\ell q} \otimes D_1 \cdot \cos\phi \\
&+ \quad \left[\frac{k_\perp^2}{Q^2} f_1 \otimes d\hat{\sigma}^{\ell q\to\ell q} \otimes D_1 + h_1^\perp \otimes d\hat{\sigma}^{\ell q\to\ell q} \otimes H_1^\perp\right] \cdot \cos 2\phi \\
&+ \quad |S_T| \cdot h_1 \otimes d\hat{\sigma}^{\ell q\to\ell q} \otimes H_1^\perp \cdot \sin(\phi + \phi_S) \quad \text{Collins} \\
&+ \quad |S_T| \cdot f_{1T}^\perp \otimes d\hat{\sigma}^{\ell q\to\ell q} \otimes D_1 \cdot \sin(\phi - \phi_S) \quad \text{Sivers} \\
&+ \quad \cdots
\end{aligned}$$

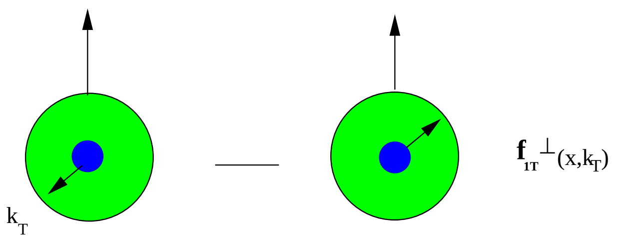
- Collins NPB:1993,
  Kotzinian NPB:1995, Mulders, Tangerman PLB:1995



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

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

(Sivers PRD: 1990, Anselmino & Murgia PLB: 1995 ...)

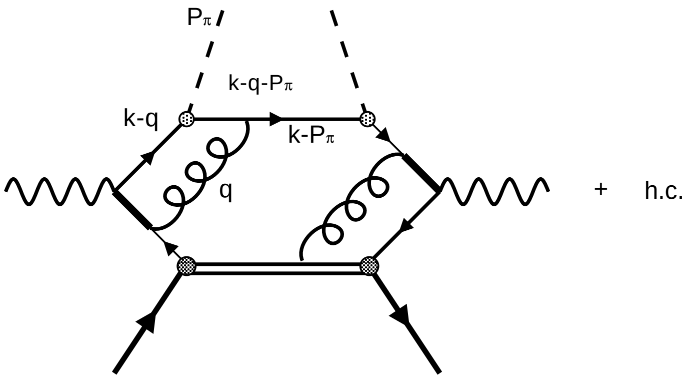


$$\langle \frac{|P_{h\perp}|}{M} \sin(\phi - \phi_S) \rangle_{UT} = |\boldsymbol{S}_T| \frac{(1 + (1-y)^2) \sum_q e_q^2 f_{1T}^{\perp(1)}(x) z D_1^q(z)}{(1 + (1-y)^2) \sum_q e_q^2 f_1(x) D_1(z)},$$

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

$\cos 2\phi$ Asymmetry Generated by ISI & FSI thru Gauge link

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



$$A_{UU}^{\cos(2\phi)} = \langle \frac{|P_{h\perp}^2|}{M M_h} \cos 2\phi \rangle_{UU}$$

$$= \frac{8(1-y) \sum_q e_q^2 h_1^{\perp(1)}(x, Q^2) z^2 H_1^{\perp(1)q}(z, Q^2)}{(1+(1-y)^2) \sum_q e_q^2 f_1^q(x, Q^2) D_1^q(z, Q^2)}$$

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

D. Boer, P. Mulders, PRD: 1998

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

$\cos 2\phi$ Asymmetry

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

Goldstein, Gamberg, ICHEP 2002; hep-ph/0209085,

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)

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

where $\Upsilon(k_\perp^2) = \mathcal{N} e^{-bk_\perp^2}.$

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

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

with

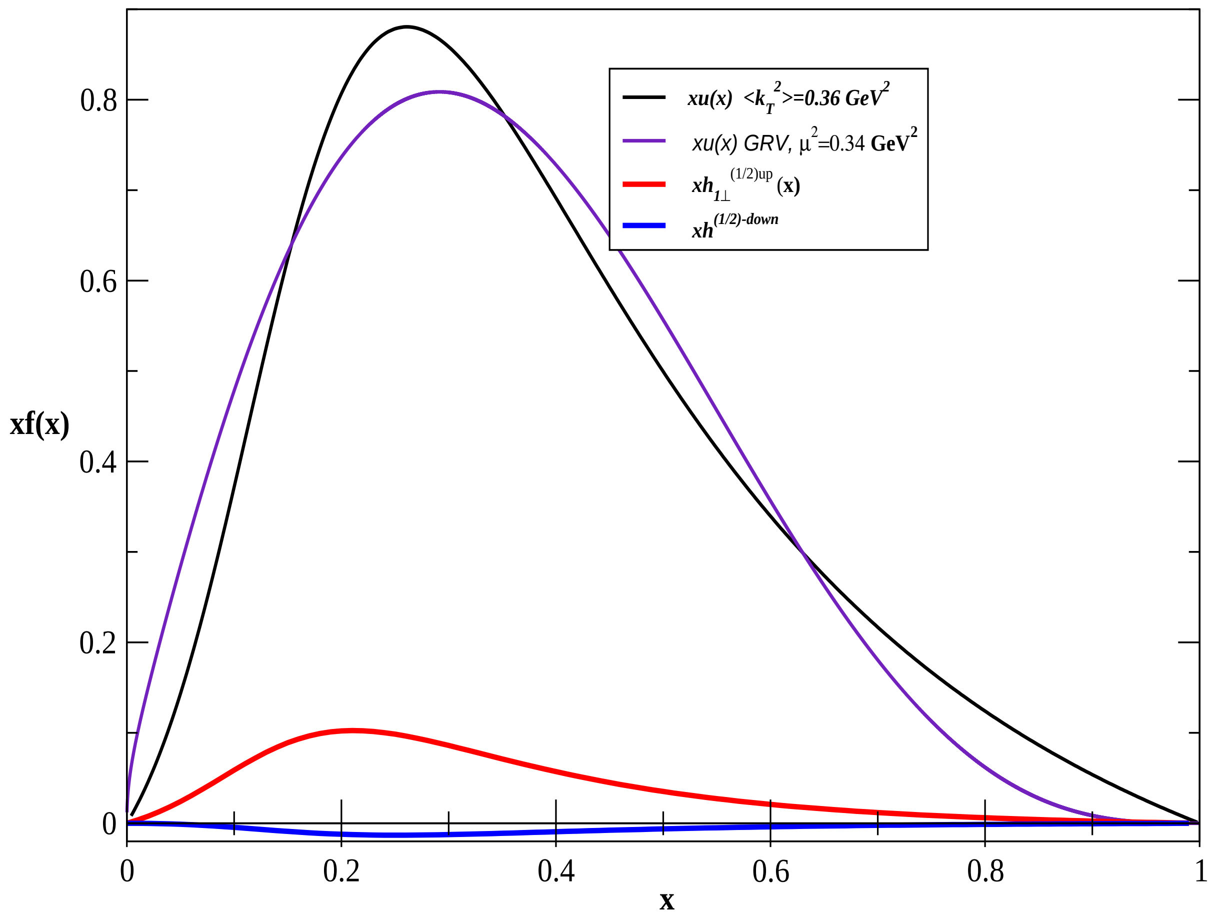
$$\mathcal{R}(k_\perp^2,x) = \exp^{-2b(k_\perp^2-\Lambda(0))}\left(\Gamma(0,2b\Lambda(0)) - \Gamma(0,2b\Lambda(k_\perp^2))\right)$$

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

INPUTS: Boer-Mulders and Unpolarized Structure Function $f_1(x)$

$$f_1(x) = \frac{g^2}{(2\pi)^2}\frac{b^2}{\pi^2}(1-x)\cdot\left\{\frac{(m+xM)^2-\Lambda(0)}{\Lambda(0)} - \left[2b\left((m+xM)^2-\Lambda(0)\right)-1\right]e^{2b\Lambda(0)}\Gamma(0,2b\Lambda(0))\right\}$$

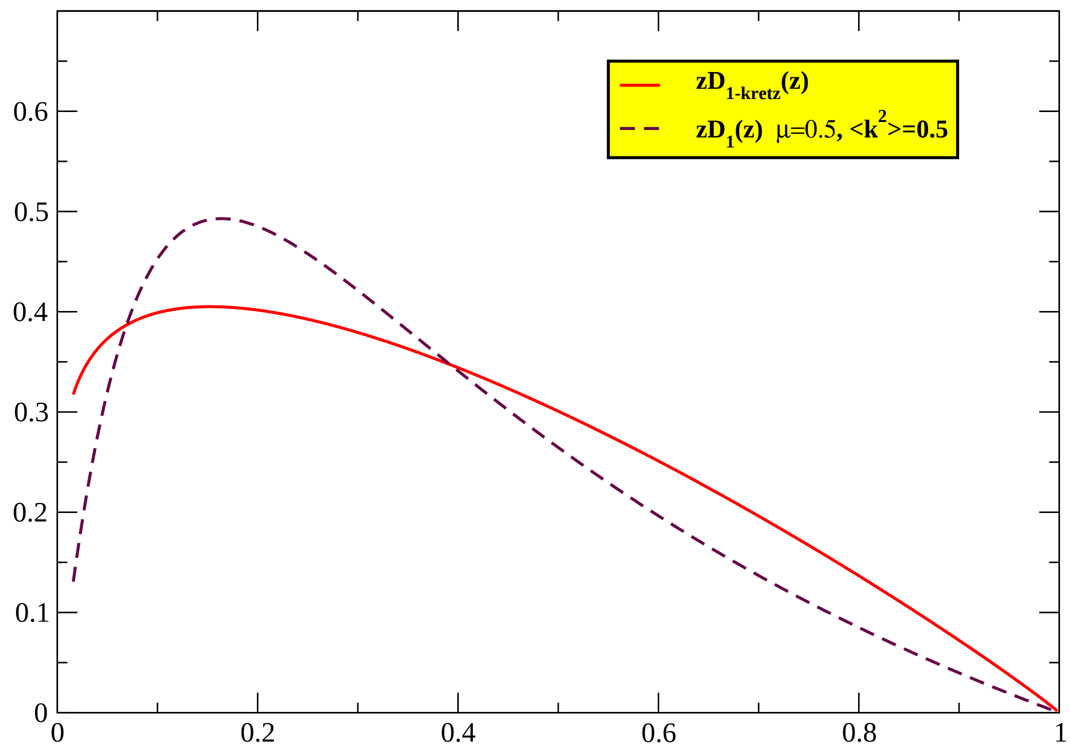
- ⋆ Normalization, $\int_0^1 u(x) = 2$
  $\int_0^1 d(x) = 1$
- Black curve- $xu(x)$
- Purple curve - $xu(x)$ GRV
- Red curve $xh_1^{\perp(1/2)(u)}$
- axial vector diquark coupling
  Jakob, Mulders, Rodrigues NPB:199
  $\gamma_5(\gamma^\mu + P^\mu/M)$



Pion Fragmentation Function

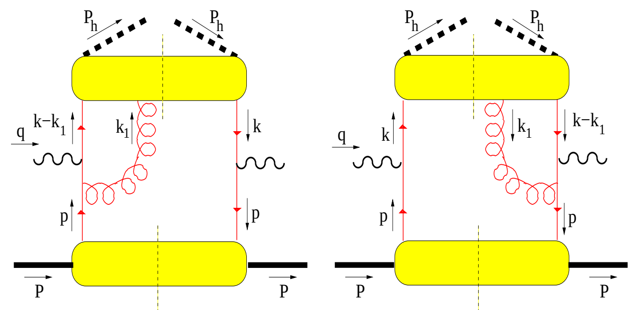
$$D_1(z) \quad = \quad \frac{{N'}^2 f_{q q\pi}^2}{4(2\pi)^2}\frac{1}{z}\frac{(1-z)}{z}\Big\{\frac{m^2-\Lambda'(0)}{\Lambda'(0)} - \Big[2b'\Big(m^2-\Lambda'(0)\Big)-1\Big]\, e^{2b'\Lambda'(0)}\Gamma(0,2b'\Lambda'(0))\Big\},$$

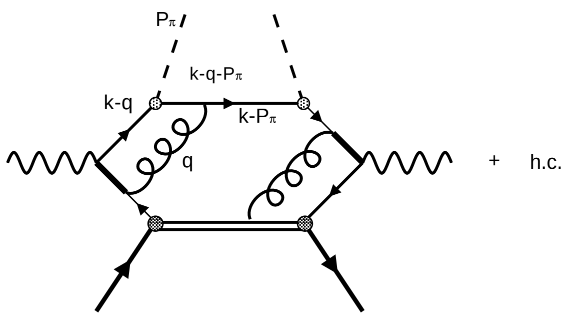
which, multiplied by z at $< k_\perp^2 >= (0.5)^2$ GeV^2 and $\mu = m$, estimates the distribution of Kretzer, PRD: 2000

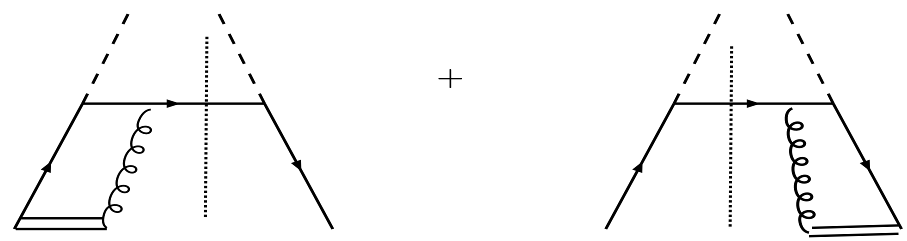


Gauge Link-Pole Contribution to T-Odd Collins Function

Gamberg,Goldstein,Oganessyan PRD68,2003 $\Delta^{[\sigma^{\perp -}\gamma_5]}(z,k_\perp) = \frac{1}{4z}\int dk^+ Tr(\gamma^-\gamma^\perp\gamma_5\Delta)|_{k^-=P_\pi^-/z}$







$\frac{i}{\ell^- - i\epsilon}$ $Eikonal\ Feynman\ Rules\ Collins$ $'82'$ $\frac{-i}{\ell^- + i\epsilon}$

Motivation:color gauge .inv frag. correlator "pole contribution"

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

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

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

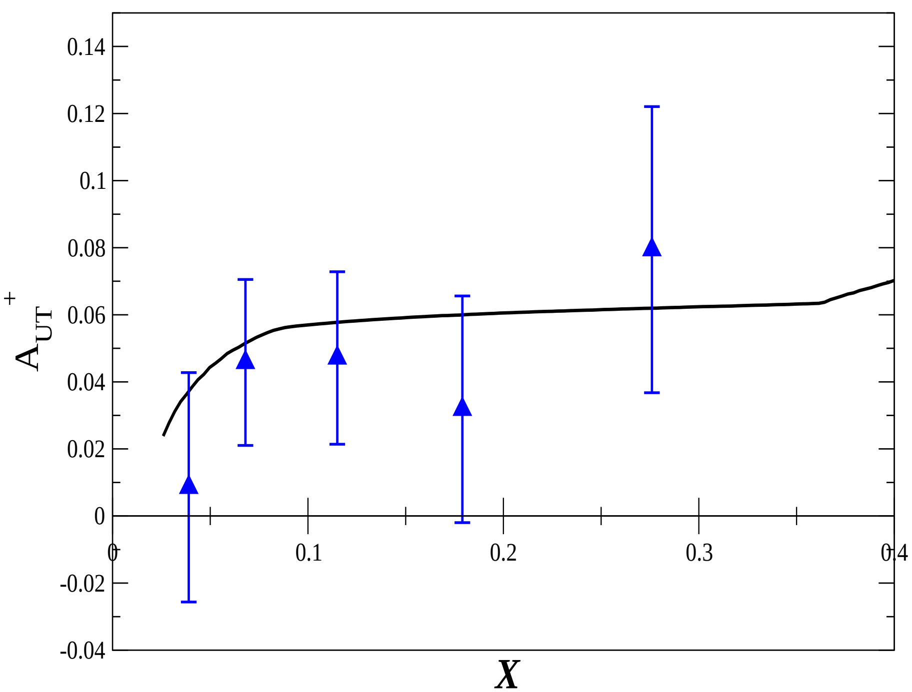
Collins Asymmetry

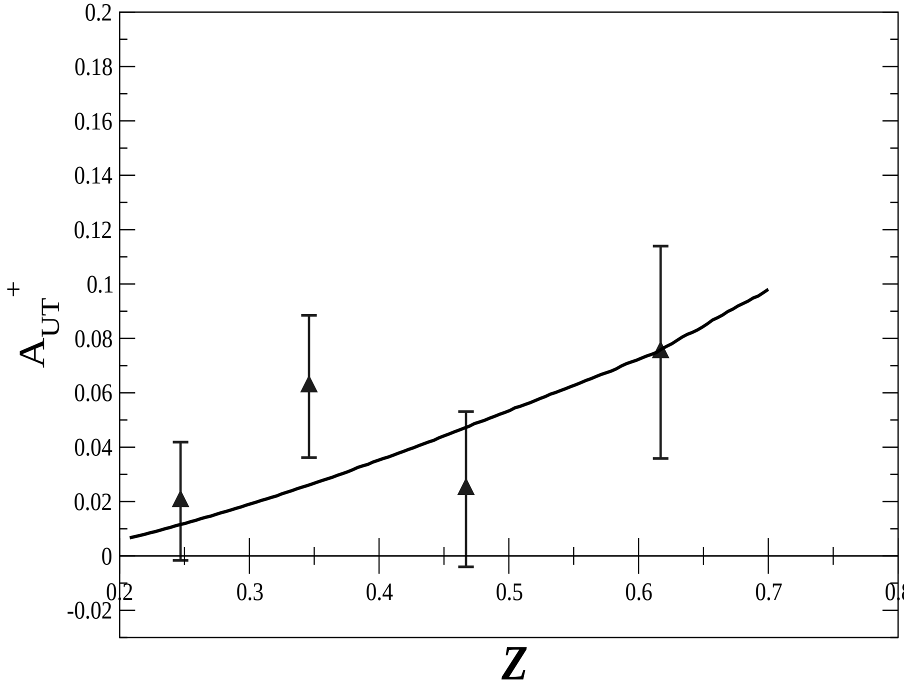
Gamberg, Goldstein, Oganessyan PRD 2003: updated For the HERMES kinematics

1 GeV$^2 \le Q^2 \le 15$ GeV^2, 4.5 GeV $\le E_\pi \le 13.5$ GeV, $0.2 \le x \le 0.41$, $0.2 \le z \le 0.7$, $0.2 \le y \le 0.8$, $< P_{h\perp}^2 >= 0.25$ GeV^2

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

Data from A. Airapetian et al. PRL94,2005



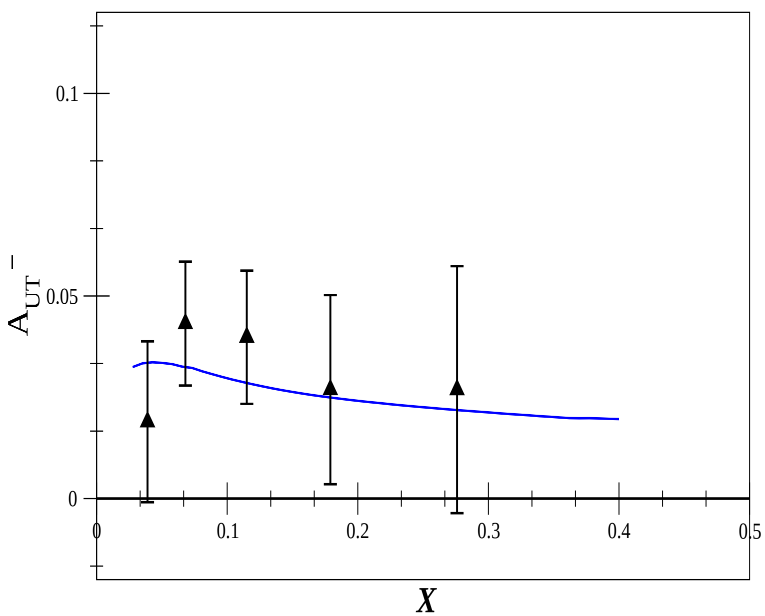


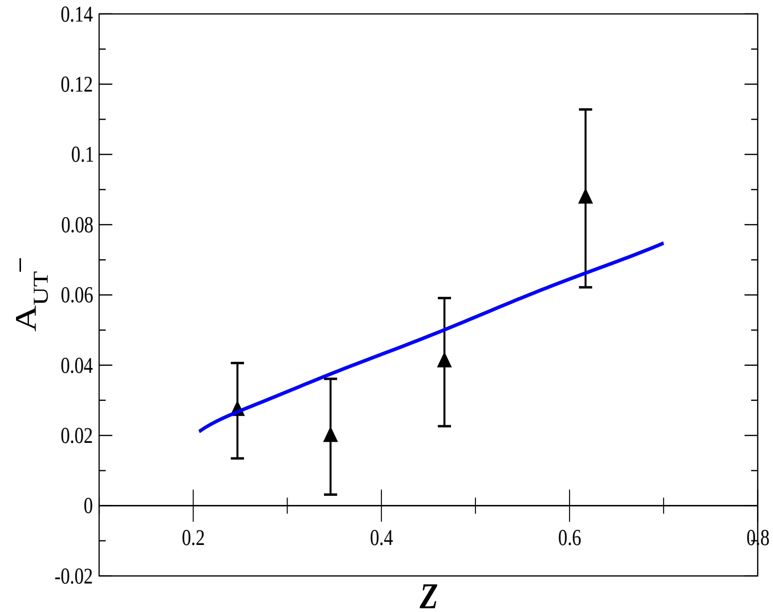
Estimates for Sivers Asymmetry

Data from A. Airapetian et al. PRL94,2005

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

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

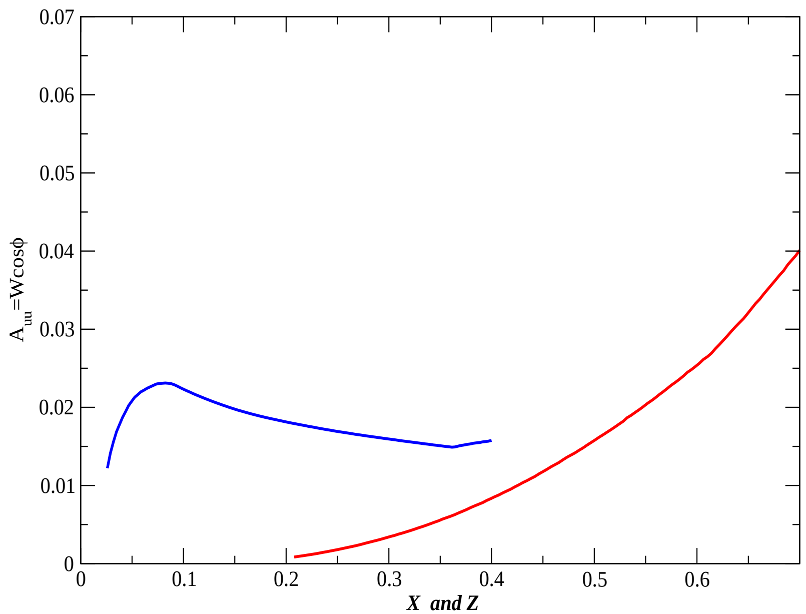




Double T-odd $\cos 2\phi$ asymmetry

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

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

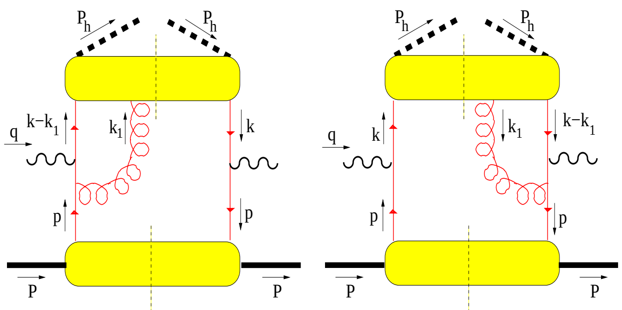


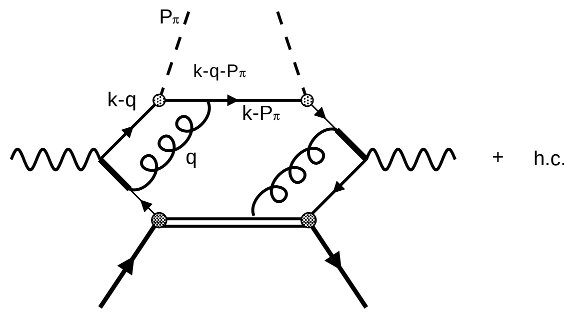
Spectator Model: Gauge Link Contribution to Collins Function

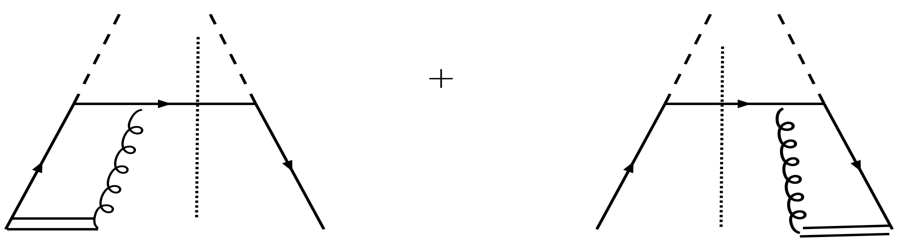
Metz: PBL 2002, Gamberg, Goldstein, Oganessyan PRD: 2003: Bacchetta, Metz, Jang: PLB: 2003, Amrath, Bacchetta, Metz:

PRD 2005, G.G. in progress

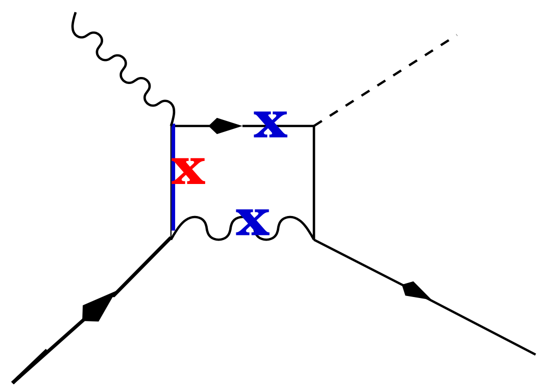
$$\Delta^{[\sigma^{\perp -}\gamma_5]}(z, k_\perp) = \frac{1}{4z}\int dk^+ \mathrm{Tr}(\gamma^- \gamma^\perp \gamma_5 \Delta)\Big|_{k^- = P_\pi^-/z}$$ Boer, Pijlman, Muders: NPB 2003







$\frac{i}{\ell^- - i\epsilon}$ *Eikonal Feynman Rules Collins* '82' $\frac{-i}{\ell^- + i\epsilon}$



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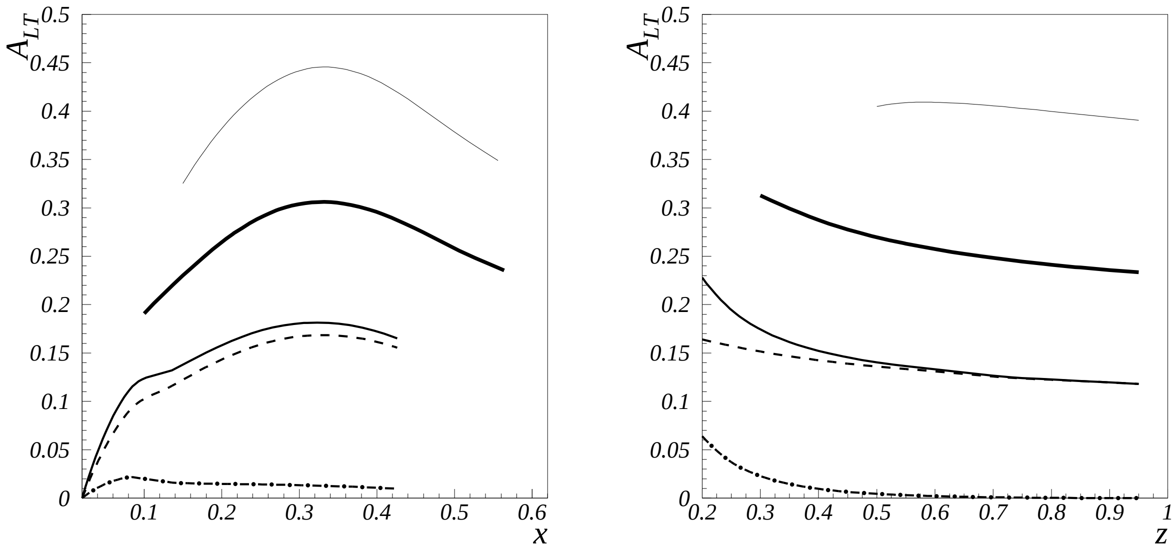
- Is the eikonal pole in the physical regime of the Collins function Correlator? and or off shell $\gamma + q \to \pi + q'$
- Explore Pole Structure of Loop Integral
  - ⋆ Using Cauchy's theorem to evaluate the Color Gauge invariant Correlator eikonal pole exists at $z = 1$: exclusive limit.
  - ⋆ Can we deform the pole away if take into account $\ell_\perp$?
  - ⋆ Evaluate the box diagram taking the eikonal limit on the fragmenting quark but keeping a mass correction: eikonal pole outside the physical regime ie $\ell^- < 0$
  - ⋆ Evaluation of Cuts in $S - channel$ w/o mass correction indicates L.C. divergence $\to \ell^- \to 0$: if regulate, cancels.
  - ⋆ ? Consistent with Correlator definition? Yes "maybe"....
  - ⋆ In correlator keep n off light cone $n \cdot A$, $n = (n^-, n^+)$ (see Ji, Yuan, Ma PLB: 2004)
  - ⋆ Pick up poles contributions on fragmenting quark and gluon $\Rightarrow$ equivalent to cut in S-channel of box.
  - ⋆ Within spectator model, em suggests Collins Function universal between e^+e^- and SIDIS.
- Earlier model calculation based color Gauge Inv. Correlator definition and transcription of fragmentation functions from distribution functions in spectator model: Jakob, Mulders, Rodrigues NPB: 1997, Bacchetta, Boffi, Jakob EJPC 2000 .

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

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

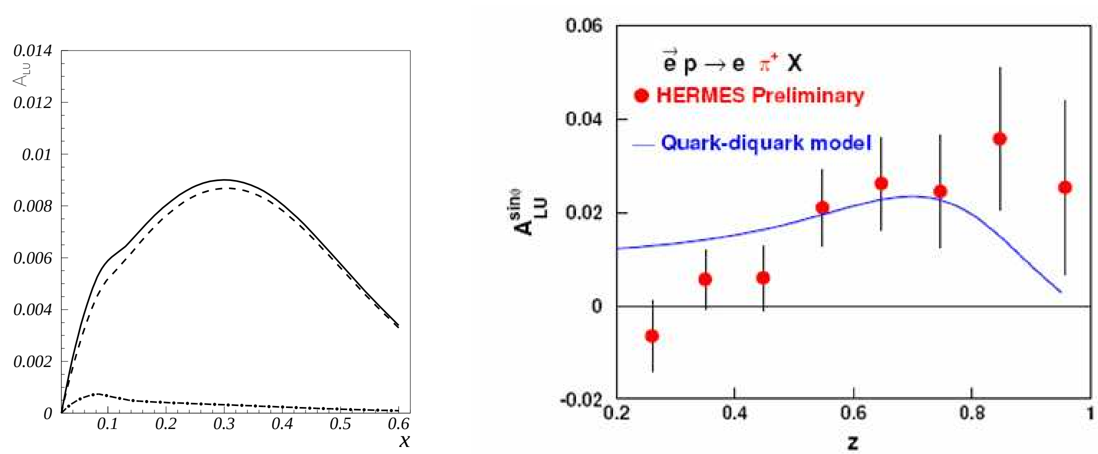


A_{LT} for π^+ production function of x and z at 27.5 GeV energy. The dashed and dot-dashed curves correspond contributions of two terms above respectively, and full curve is sum. Thin curve corresponds to 6 GeV and the thick to 12 GeV energies.

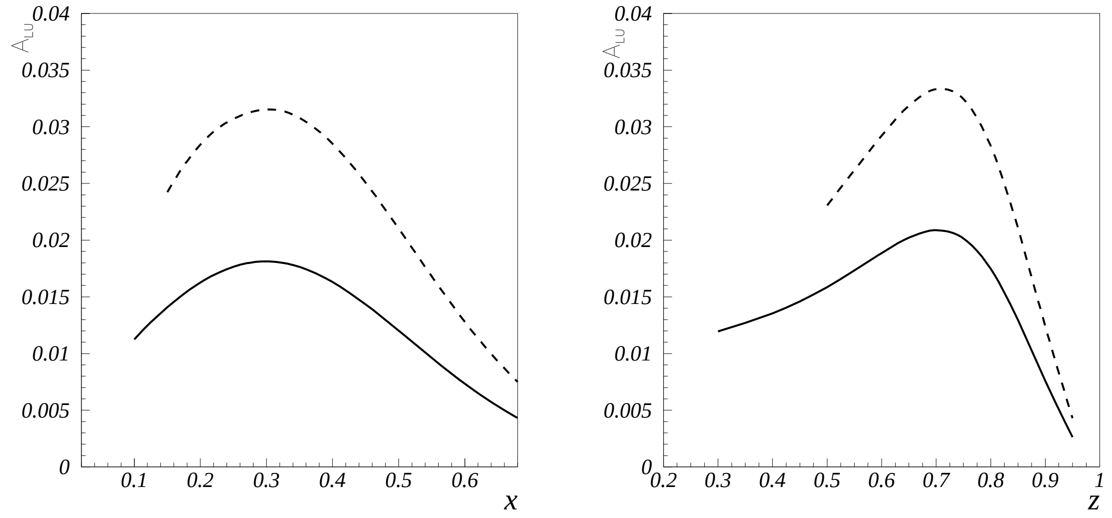
⋆ Bean Asymmetry Estimate of this effect, Gamberg, Hwang, Oganessyan PLB:2004

F. Yuan, PLB: 2004. Metz and Schleigel, hep-ph/0403182, Bacchetta *et al* hep-ph/0405154. extra terms $g^{\perp}$? how big?

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



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



JLAB Kin. 6 and 12 GeV

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 SDIS and Drell Yan from the standpoint 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