“T-Odd Transverse Quark-Spin Effects”

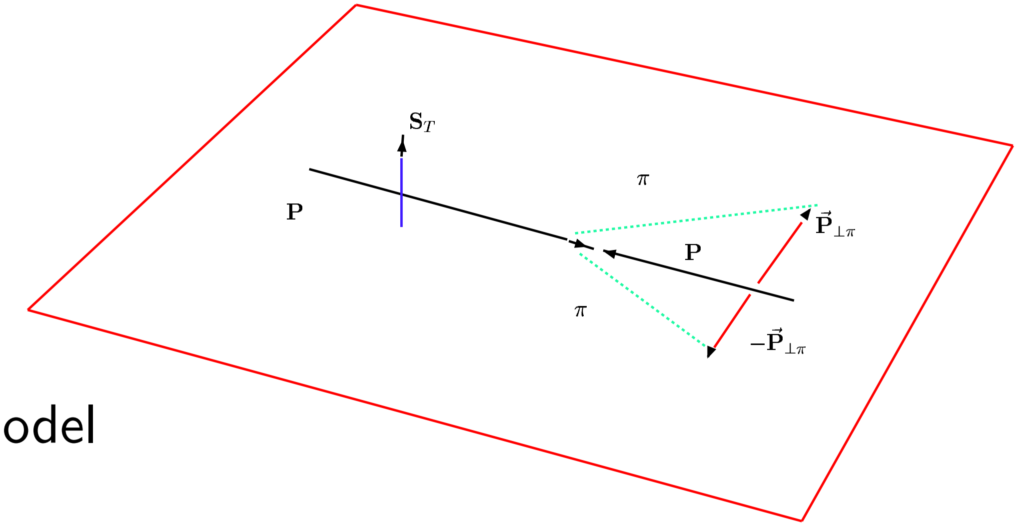
Leonard Gamberg*
Penn State Berks

Inclusive and Semi-Inclusive Spin Physics with High Luminosity and Large Acceptance at 11 GeV

- Remarks Transverse Spin effects in TSSAs and AAs in QCD
- ⋆ Reaction Mechanisms: Colinear-limit ETQS-Twist Three, Beyond Co-linearity ISI/FSI Twist Two
- ⋆ Unintegrated PDF “T-odd” TMDs Distribution and Fragmentation Functions
  Correlations btwn intrinsic $k_\perp$, transverse spin S_T
- ⋆ T-odd $\cos 2\phi$ asymmetry in SIDIS & DRELL-YAN
- Conclusions

[*] G. R. Goldstein (Tufts), Andreas Metz, Marc Schlegel (Bochum), A. Bacchetta (DESY), A. Mukherjee (ITT, Bombay), D.S. Hwang (Seoul)

Transverse SPIN Observables SSA (TSSA)



$$\Delta\sigma \sim i\mathbf{S}_T\cdot(\mathbf{P}\times\boldsymbol{P}_{\pi\perp})$$

- ⋆ Co-linear factorized QCD-parton model
  $\Delta\sigma \sim f_a \otimes f_b \otimes \hat{\sigma} \otimes D^{q\to\pi}$
  Requires helicity flip in hard part $\hat{\sigma}$

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

- ⋆ Requires relative phase btwn helicity amps

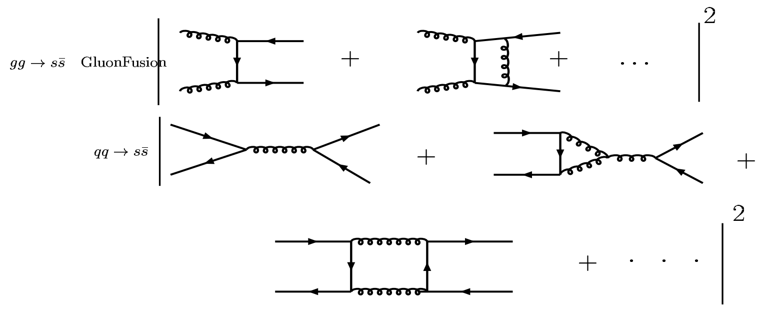
- • "TRIVIALITY" QCD interactions conserve helicity $m_q \to 0$
  & Born amplitudes are real!

- ⋆ Generically, Interference btwn loops-tree level $A_N \sim m_q\alpha_s/P_T$
  Kane, Repko, PRL:1978

Early test-Λ Production $(pp \to \Lambda^{\uparrow} X)$ Dharmartna & Goldstein PRD 1990

- Need strange quark to polarize a Λ

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



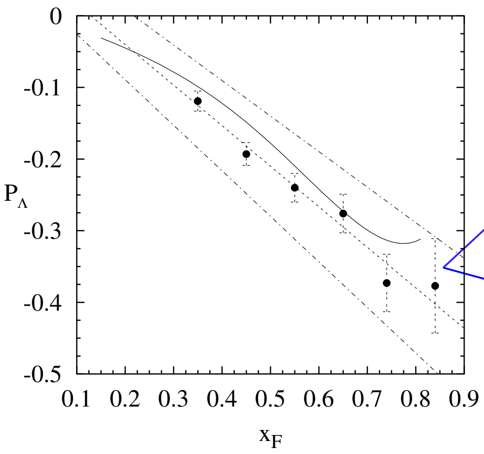
Phases in hard part
interference of loops and tree level

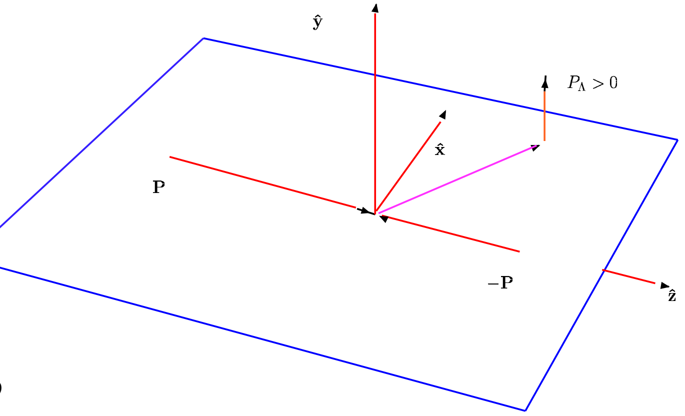
- Polarization $P_\Lambda \sim m_s \alpha_s / P_T$–twist 3 & small $\approx 5\%$ as predicted

- Experiment *glaringly at odd with this result*

P_Λ in $p - p$ scattering-Fermi Lab

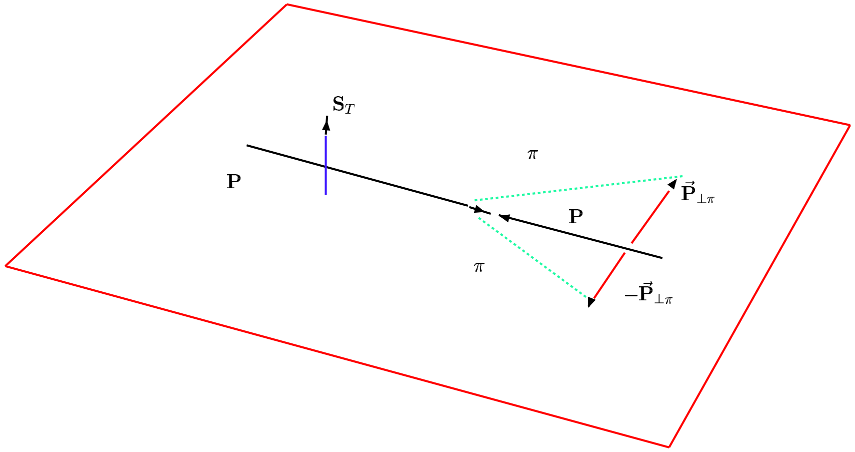
Heller,...,Bunce PRL:1983

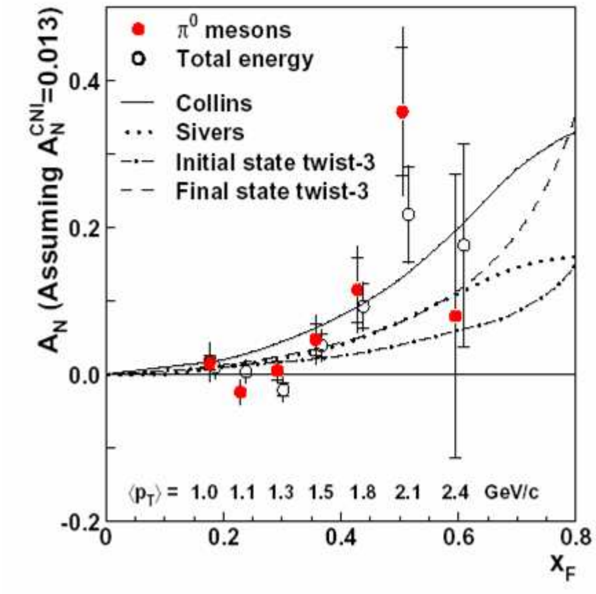


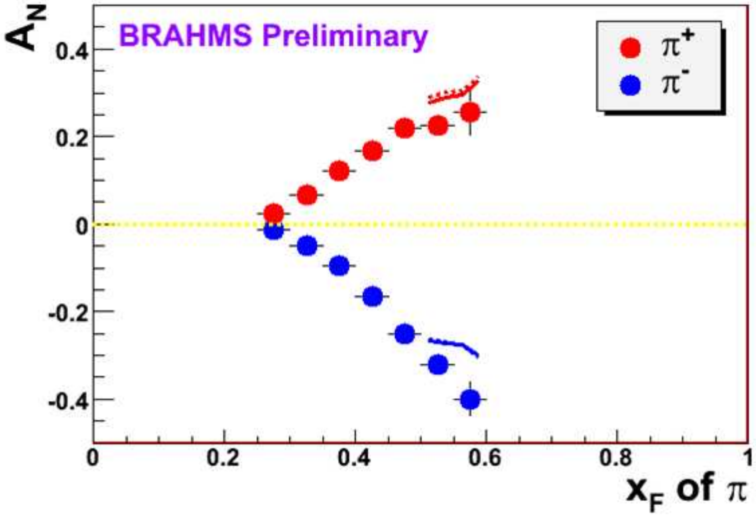


LARGE TSSAS OBSERVED: E704-Fermi Lab, RHIC $p^{\uparrow}p \rightarrow \pi\ X$

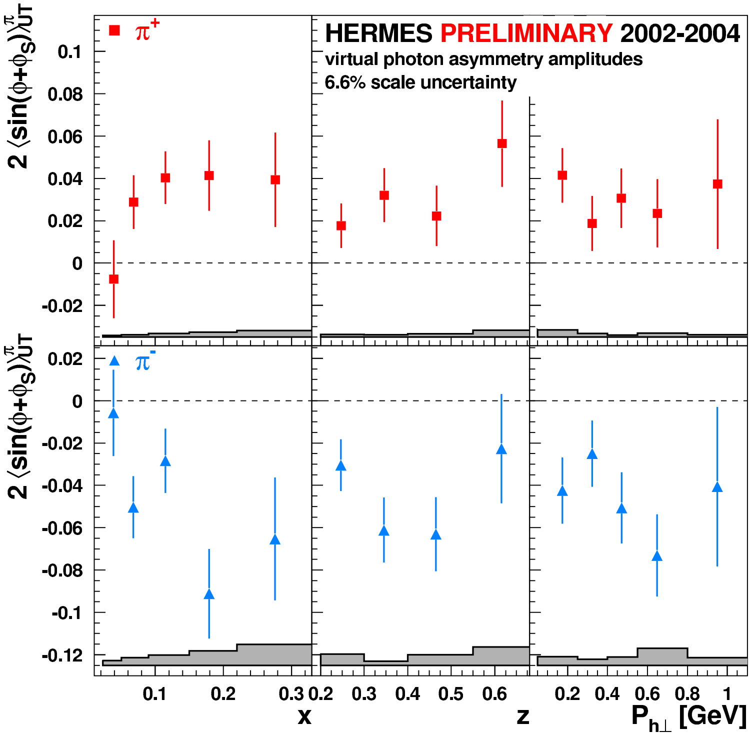
L-R asymmetry of π production and A_N for π_0 production at STAR : PRL 2004

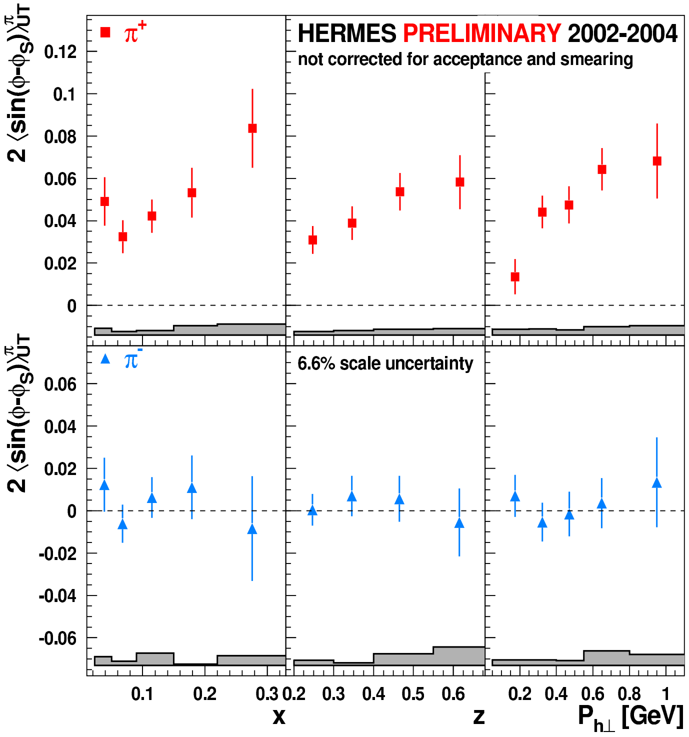


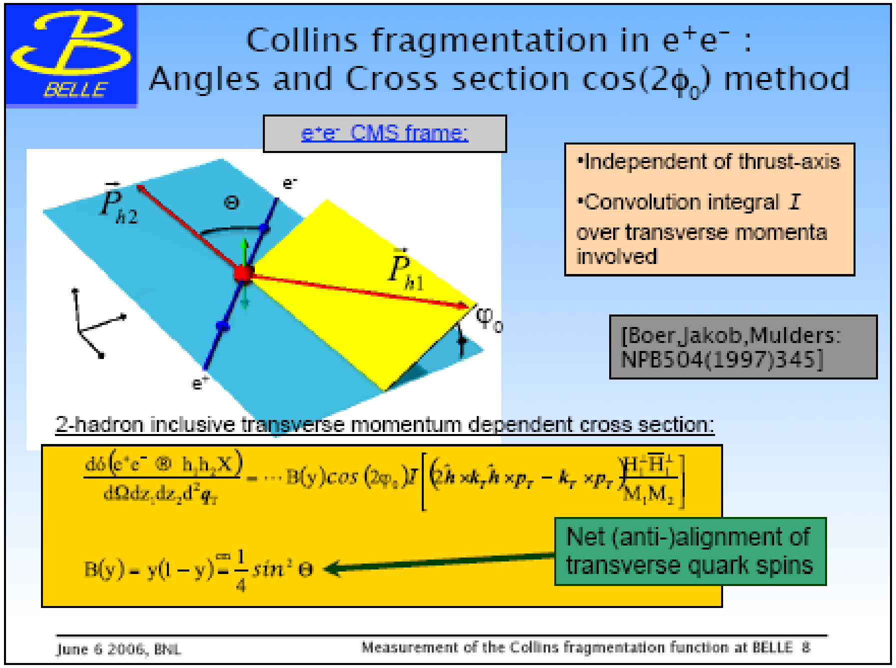




HERMES SIDIS $e\ p^{\uparrow} \to \pi\ X$







Collins fragmentation in e^+e^- : Angles and Cross section $\cos(2\phi_0)$ method

e⁺e⁻ CMS frame:

- Independent of thrust-axis
- Convolution integral *I* over transverse momenta involved

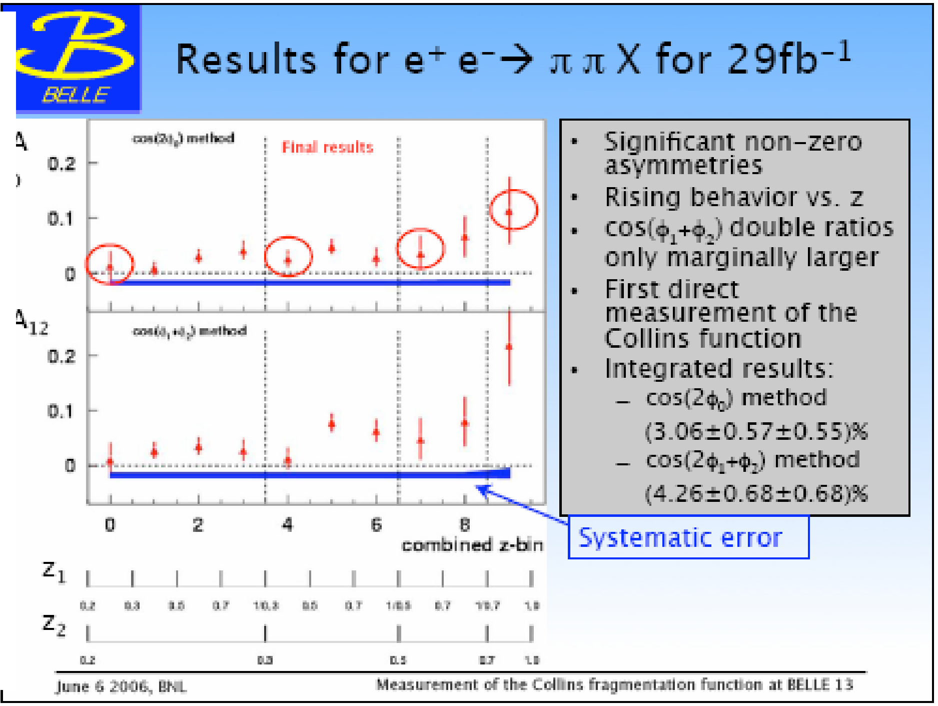
[Boer,Jakob,Mulders: NPB504(1997)345]

2-hadron inclusive transverse momentum dependent cross section:

$$\frac{d\hat{\sigma}\left(e^+e^- \otimes h_1h_2X\right)}{d\Omega dz_1 dz_2 d^2\boldsymbol{q}_T} = \cdots B(y)\cos(2\varphi_0)I\left[\left(2\hat{h}\times\boldsymbol{k}_T\hat{h}\times\boldsymbol{p}_T - \boldsymbol{k}_T\times\boldsymbol{p}_T\right)\frac{H_1^\perp\overline{H}_1^\perp}{M_1M_2}\right]$$

$$B(y) = y(1-y)\overset{cm}{=}\frac{1}{4}\sin^2\Theta$$

Net (anti-)alignment of transverse quark spins

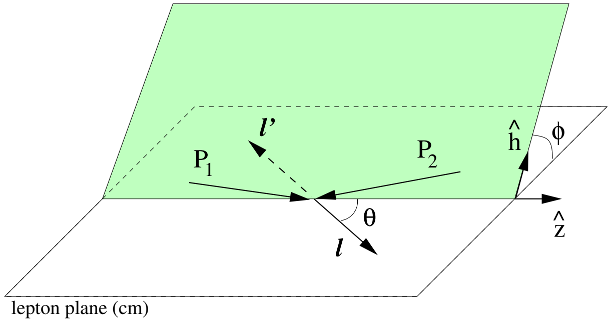


Results for $e^+ e^- \rightarrow \pi\,\pi\,X$ for 29fb^{-1}

- Significant non-zero asymmetries
- Rising behavior vs. z
- $\cos(\phi_1+\phi_2)$ double ratios only marginally larger
- First direct measurement of the Collins function
- Integrated results:
  - $\cos(2\phi_0)$ method $(3.06\pm0.57\pm0.55)\%$
  - $\cos(2\phi_1+\phi_2)$ method $(4.26\pm0.68\pm0.68)\%$

Systematic error

Azimuthal Asymmetry–Unpolarized DRELL YAN



$\pi^- + p \longrightarrow \mu^+ + \mu^- + X$

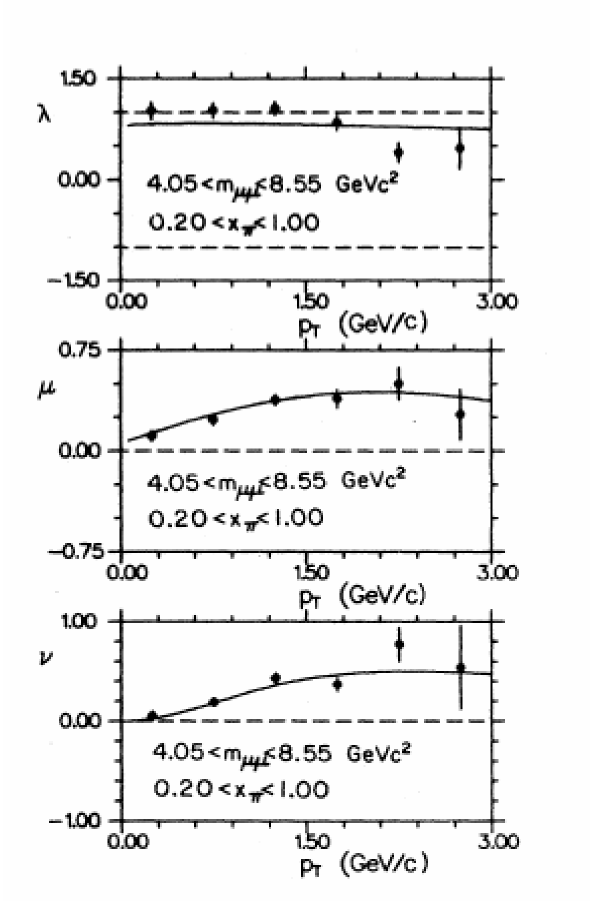
E615,Conway et al. 1986, NA10, ZPC, 1986

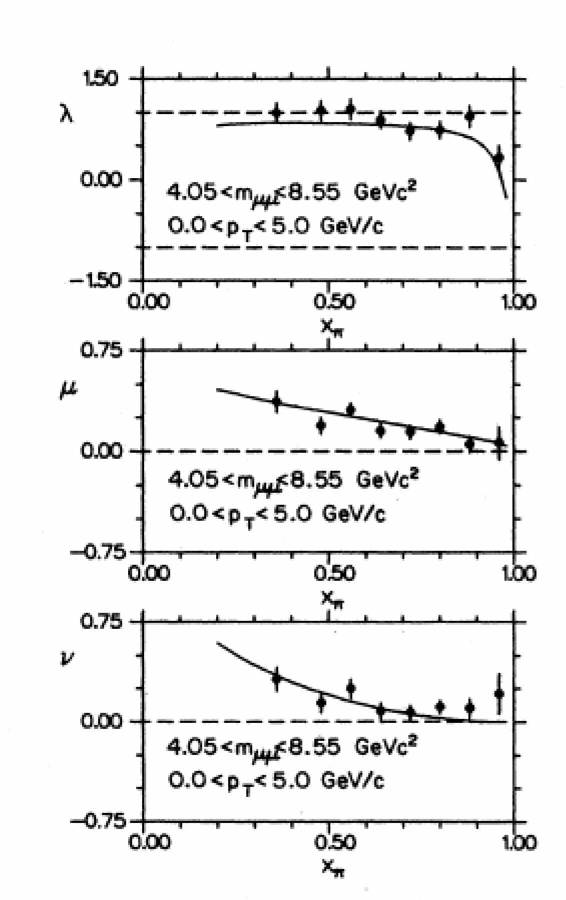
QCD-Parton Model doesn't account for large "AA"

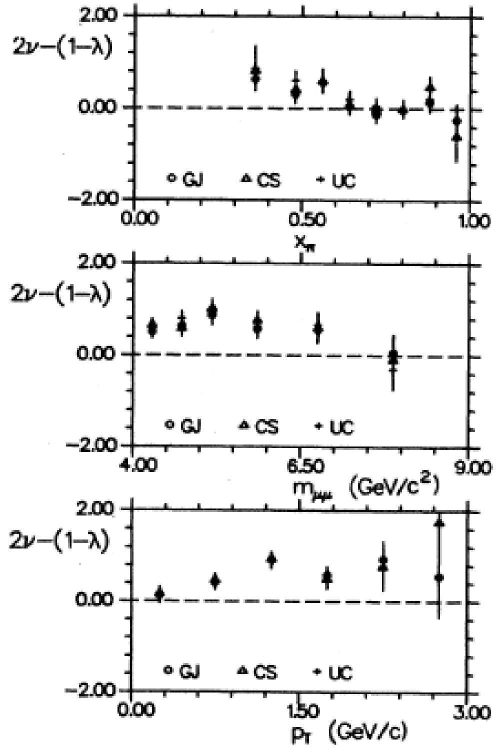
$\lambda,\ \mu,\ \nu$ **depend on** $s, x, m^2_{\mu\mu}, p_T$

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

- NNLO QCD predict Lam-Tung relation $1-\lambda-2\nu=0$ (Mirkes Ohnemus, PRD 1995)
- AND *unexpected large* $\cos 2\phi$–$\nu \sim 10-30\%$ AA







Lam-Tung Relationship Violated

When $P_T >> \Lambda_{qcd}$ Co-linear Twist Three Mechanism

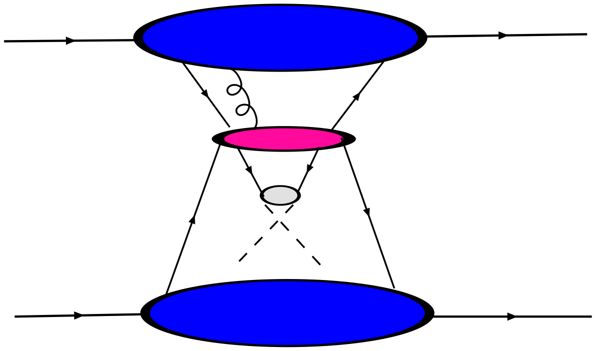
Phases generated poles in propagator of hard parton subprocess

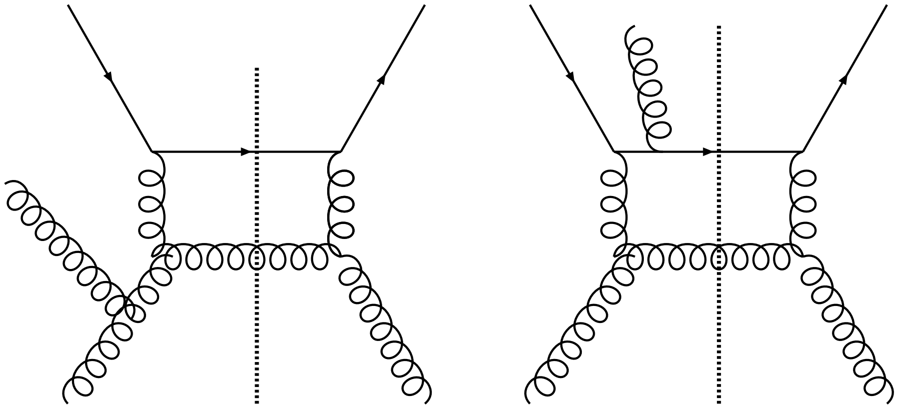
Efremov & Teryaev :PLB 1982

$\star$ Get helicity flips and phases, $m_q \to\sim M_H$ and
$\star$ $\alpha_s \to$ correlation function-*Sounds familiar* !

- $\Delta\sigma \sim f_a \otimes T \otimes H_{ETQS} \otimes D^{q\to\pi}$ Factorized co-linear QCD

  Qiu & Sterman :PLB 1991, 1999 Koike & Kanazawa:PLB 2000, Ji,Qiu,Vogelsang,Yuan:PR 2006

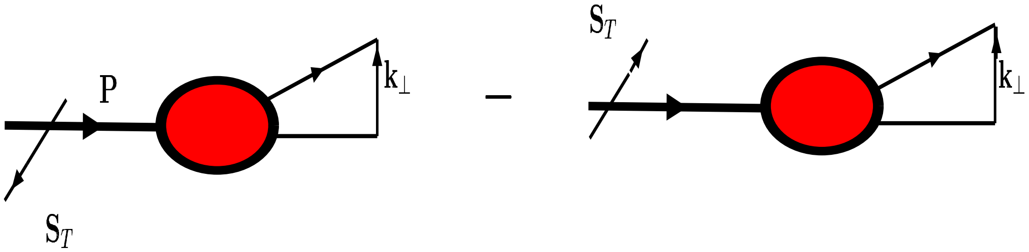




$$\Rightarrow \quad \frac{1}{xs \pm i\epsilon} = \mathcal{P}\left(\frac{1}{xs}\right) \mp i\pi\delta(xs)$$

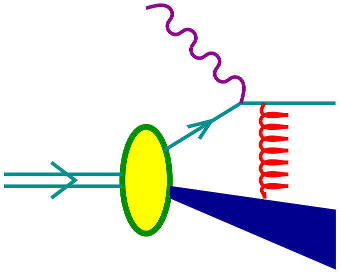
$\boldsymbol{p}_T \sim k_\perp$ TSSAs thru "T-Odd" TMD

- Sivers PRD: 1990, Anselmino & Murgia PLB: 1995 TSSA associated with "T-odd" correlation of *transverse* spin and momenta Correlation accounts for left-right TSSA



$$\Delta\sigma \sim D \otimes f \otimes \Delta f^{\perp} \otimes \hat{\sigma}_{Born} \quad i\boldsymbol{S}_T \cdot (\boldsymbol{P} \times \boldsymbol{k}_\perp) \rightarrow f_{1T}^{\perp}(x, \boldsymbol{k}_\perp)$$

- SIDIS w/ transverse polarized nucleon target $e\ p^{\perp} \rightarrow \pi X$
  Brodsky, Hwang, Schmidt PLB: 2002 FSI produce phase in TSSAs-*Leading Twist*
  Ji, Yuan PLB: 2002 -Sivers fnct. FSI emerge from Color Gauge-links

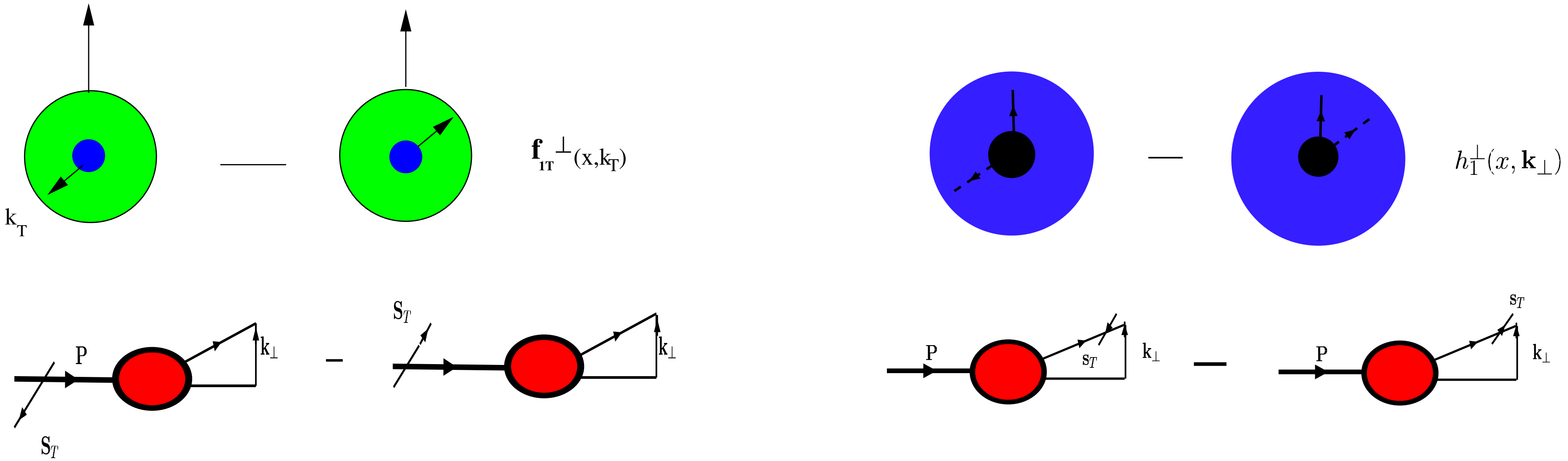


- Collins NPB 1993 "T-odd" correlation transversely polarized fragmenting quark: TSSA in lepto-production $is_T \cdot (\boldsymbol{p} \times \boldsymbol{P}_{\pi\perp}) \rightarrow H_1^{\perp}(z, \boldsymbol{p}_\perp)$

“T-odd” Correlation of Transversely polarized quark

Transversity w/o Target Polarization

Boer and Mulders PRD: 1998 “T-odd” correlation of transversely polarized *quark spin* with intrinsic $\boldsymbol{k}_\perp$ $\quad i s_T \cdot (\boldsymbol{k}_\perp \times \boldsymbol{P}) \rightarrow h_1^\perp(x, \boldsymbol{k}_\perp)$



$h_1^\perp(x, k_\perp)$ number density transversely polarized quarks in unpolarized nucleons

- ⋆ Boer, Mulders PRD: 1998 $\cos 2\phi$-AA in unpolarized lepto-production $e\,P \rightarrow e'\,\pi\,X$
- ⋆ Boer PRD: 1999 Drell Yan: $\pi^- + p \rightarrow \mu^+ + \mu^- + X$ or $\bar{p} + p \longrightarrow \mu^-\mu^+ + X$ (cleaner-no Fragmentation)

Provide source of T-Odd Contributions to TSSA and AA

- "T-odd" distribution-fragmentation functions enter transverse momentum dependent correlators at *leading twist* Boer, Mulders: PRD 1998

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

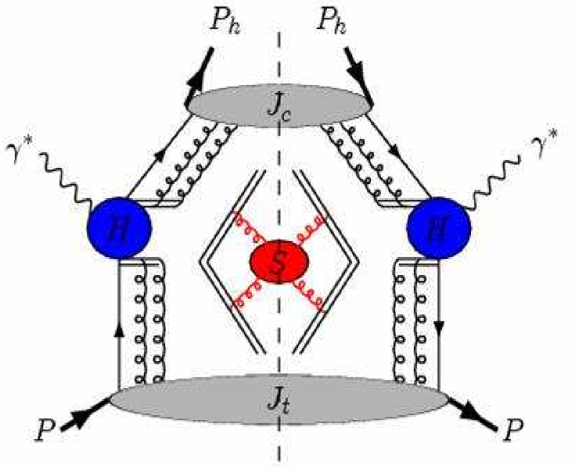
$$\Phi(x,\boldsymbol{p}_\perp)=\frac{1}{2}\{f_1(x,\boldsymbol{p}_\perp)\not{n}_+ + h_1^\perp(x,\boldsymbol{p}_\perp)\frac{\sigma^{\alpha\beta}p_{T\alpha}n_{+\beta}}{M} + f_{1T}^\perp(x,\boldsymbol{p}_\perp)\frac{\epsilon^{\mu\nu\rho\sigma}\gamma^\mu n_+^\nu p_\perp^\rho S_T^\sigma}{M}\cdots\}$$

SIDIS cross section

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

Factorization For TMD- PDF and FF and Hard Soft Parts

Ji, Ma, Yuan: PLB, PRD 2004, 2005 building on Collins-Soper NPB: 81, extend factorization theorems to 1-loop-beyond

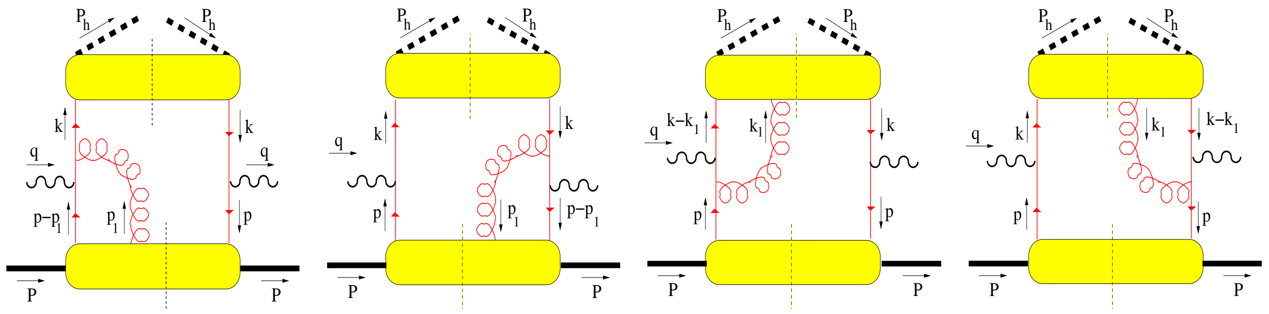


Collins and Metz: PRL 2005, *Universality & Factorization "Maximally" Correlated*

T-Odd Effects Incorp. Color Gauge Invariant Factorized QCD leading twist thru Wilson Line

- Gauge Invariant Distribution and Fragmentation Functions

  Boer, Mulders: NPB 2000, Ji et al PLB: 2002, NPB 2003, Boer et al NPB 2003



etc . . .

Sub-class of loops in eikonal limit sum up to yield color gauge invariant hadronic tensor *factorized* into distribution Φ and fragmentation Δ operators

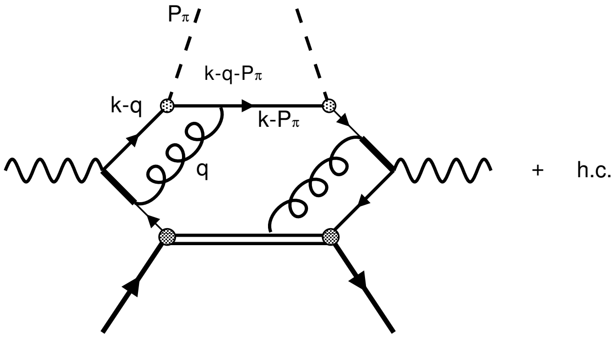
$$\Phi(p,P)=\int\frac{d^3\xi}{2(2\pi)^3}e^{ip\cdot\xi}\langle P|\overline{\psi}(\xi^-,\xi_\perp)\mathcal{G}^\dagger_{[\xi^-,\infty]}|X\rangle\langle X|\mathcal{G}_{[0,\infty]}\psi(0)|P\rangle|_{\xi^+=0}$$

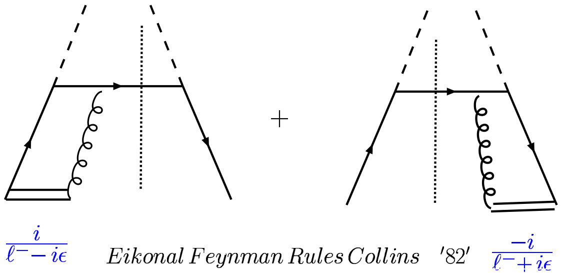
$$\Delta(k,P_h)=\int\frac{d^3\xi}{4z(2\pi)^3}\ e^{ik\cdot\xi}\ \langle 0\ |\mathcal{G}_{[\xi^+,-\infty]}\psi(\xi)|X;P_h\rangle\langle X;P_h|\overline{\psi}(0)\mathcal{G}^\dagger_{[0,-\infty]}|0\rangle|_{\xi^-=0}$$

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

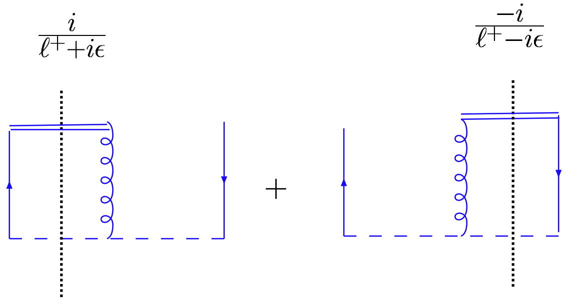
$\cos 2\phi$ Asymmetry Convolution of ISI & FSI thru Gauge link

G. Goldstein, L.G.–ICHEP-2002 hep-ph/0209085, L.G,G.G., Oganessyan PRD:2003, Como-PROC. 2006





Eikonal Feynman Rules Collins '82'



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

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

Estimates of T-odd Contribution in SIDIS (HERMES, JLAB 6 & 12 GeV program)

$\cos 2\phi$ Asymmetry in SIDIS-Boer Mulders Effect

⋆ Spectator framework in BHS Ji-Yuan point-like nucleon-quark-diquark vertex logarithmically divergent asymmetries, Goldstein, L.G., ICHEP 2002; hep-ph/0209085)

$$h_1^{\perp(s)}(x,k_\perp) \quad = \quad f_{1T}^{\perp(s)}(x,k_\perp)$$

- Asymmetry-weighted function $h_1^{(1)\perp}(x) \equiv \int d^2k_\perp \frac{k_\perp^2}{2M^2} h_1^\perp(x,k_\perp^2)$ *diverges*
- Gaussian Distribution in $k_\perp$ L.G., Goldstein, Oganessyan, PRD 67 (2003)

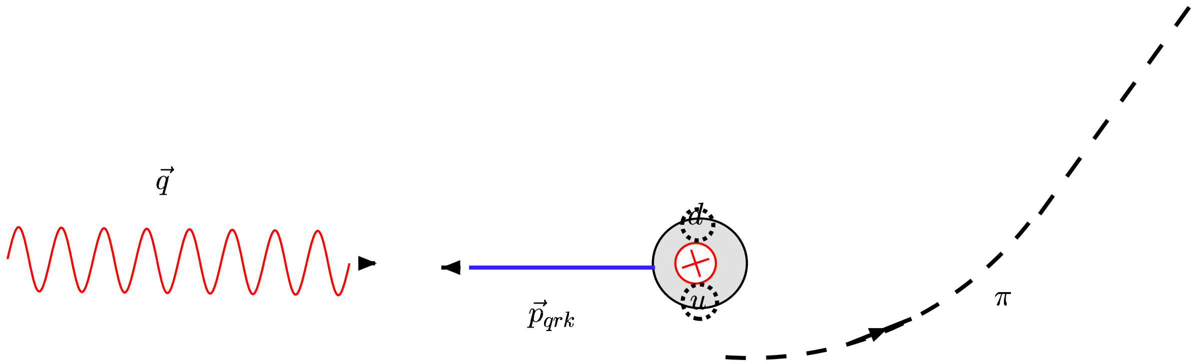
$$h_1^\perp(x,k_\perp) \quad = \quad \alpha_s \mathcal{N}_s \frac{M(m+xM)(1-x)}{k_\perp^2 \Lambda(k_\perp^2)} \mathcal{R}(k_\perp^2,x)$$

with

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

Quark Transversity, Boer Mulders Function GPDs-Impact Parameter TMDs

- Correlations transverse-spin & intrinsic $k_\perp$ serves fix sign Boer Mulders



- $\delta q^X(x, \mathbf{b}_\perp) \leftrightarrow h_1^{\perp q}$ WHERE $\delta q^X(x, \mathbf{b}_\perp) = -\frac{1}{2M}\frac{\partial}{\partial\, b_y}(2\tilde{\mathcal{H}}_T(x, \mathbf{b}_\perp) + \mathcal{E}_T(x, \mathbf{b}_\perp))$
  - ⋆ $d_y^q = \int dx \int d^2\mathbf{b}_\perp \delta q^X(x, \mathbf{b}_\perp) b_y = \kappa_T^q / 2M$

- *Transverse distortion* in impact parameter space of transversly polarized quarks in an unpolarized nucleon Burkardt PRD 2005, Diehl, Hägler EPJC 2005

⋆ Implies up and down quark Boer Mulders function-same sign!

Deformed quark densities and spin asymmetries

Sivers - function $f_{1T}^{\perp}(x,p_{\perp})$ probes correlation of transverse nucleon spin and intrinsic transverse momentum

$$f_{1Tq}^{\perp}(x,p_{\perp}) \sim -\int dx E_q(x,0,0) = -B_{10,q}(0) = -\kappa_q$$

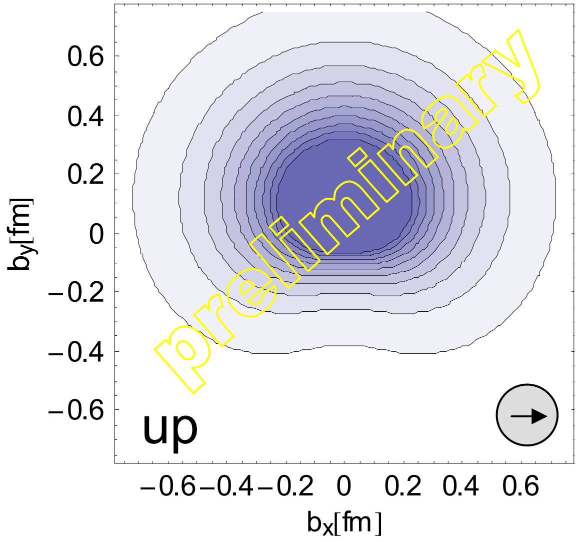
Burkardt PRD 2005

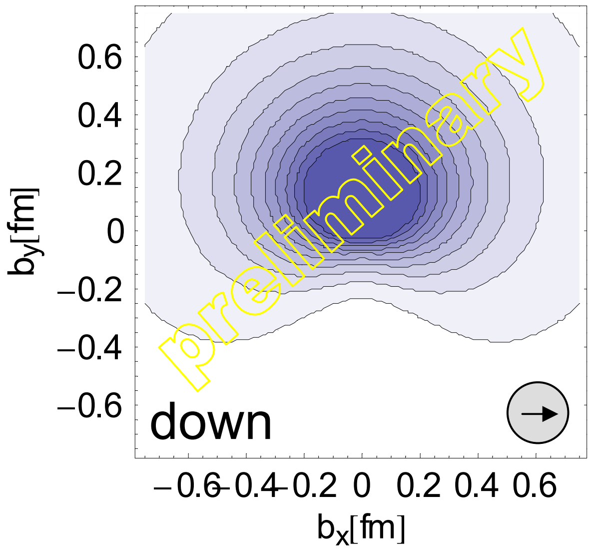
Boer - Mulders - function $h_1^{\perp}(x,p_{\perp})$ probes correlation of transverse quark spin and intrinsic transverse momentum

$$h_{1q}^{\perp}(x,p_{\perp}) \sim -\int dx \overline{E}_{Tq}(x,0,0) = -\overline{B}_{T10,q}(0)$$

$$\overline{B}_{T(u,d),lattice}(0) \approx 2\ldots3$$

⇒





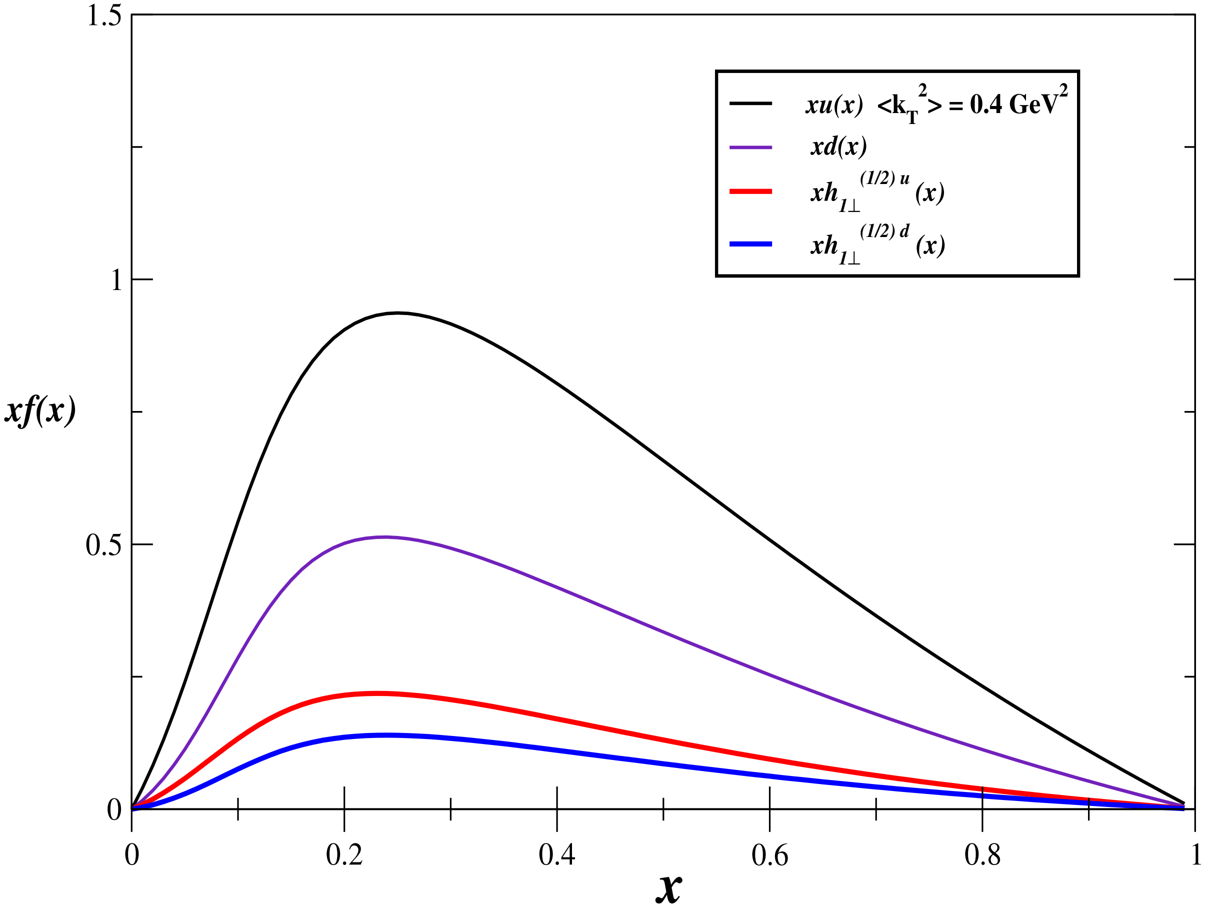
⇓

could imply to sizeable Boer-Mulders-effect

Spectator Framework: Boer-Mulders $h_1^{\perp(1/2)}$ and Unpolarized $f_1(x)$

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

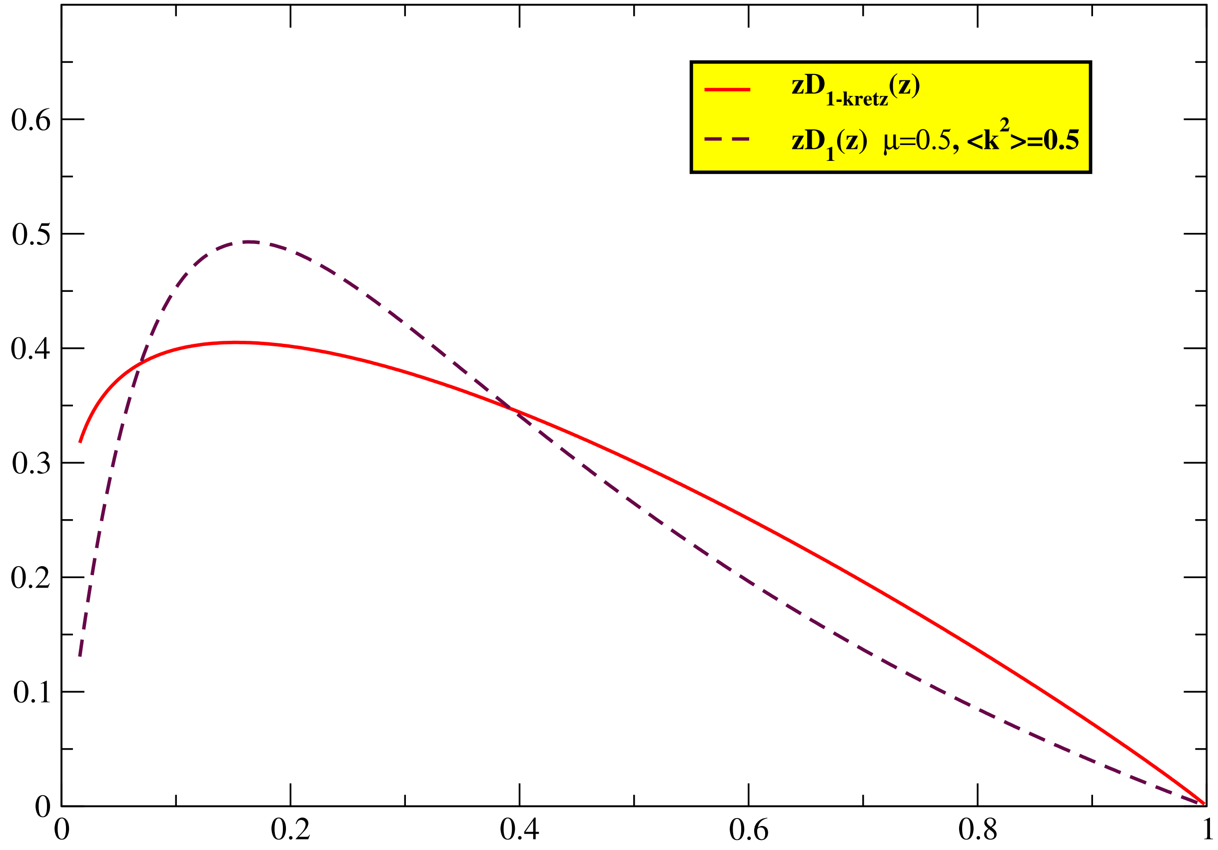
- ⋆ Valence Normalization, $\int_0^1 u(x) = 2$, $\int_0^1 d(x) = 1$
- ● Black curve- $xu(x)$
- ● Dashed curve - $xu(x)$ GRV
- ● Red/Blue curve $xh_1^{\perp(1/2)(u,d)}$



Pion Fragmentation Function

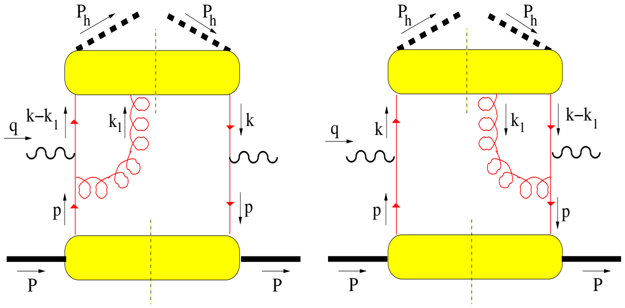
$$D_1(z) = \mathcal{N}' \frac{(1-z)}{z^2} \left\{ \frac{m^2 - \Lambda'(0)}{\Lambda'(0)} - \left[2b' \left(m^2 - \Lambda'(0) \right) - 1 \right] e^{2b'\Lambda'(0)} \Gamma(0, 2b'\Lambda'(0)) \right\}$$

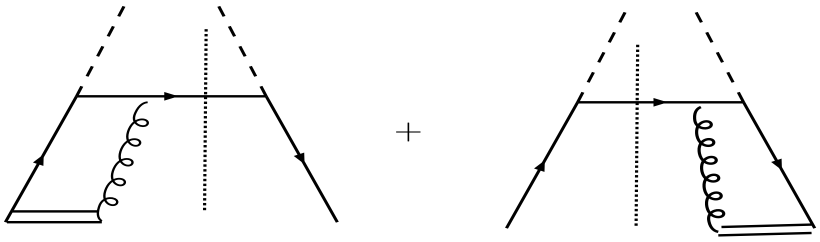
Normalized to Kretzer, PRD: 2000



Gauge Link Contribution to T-Odd Collins Function

L.G.,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

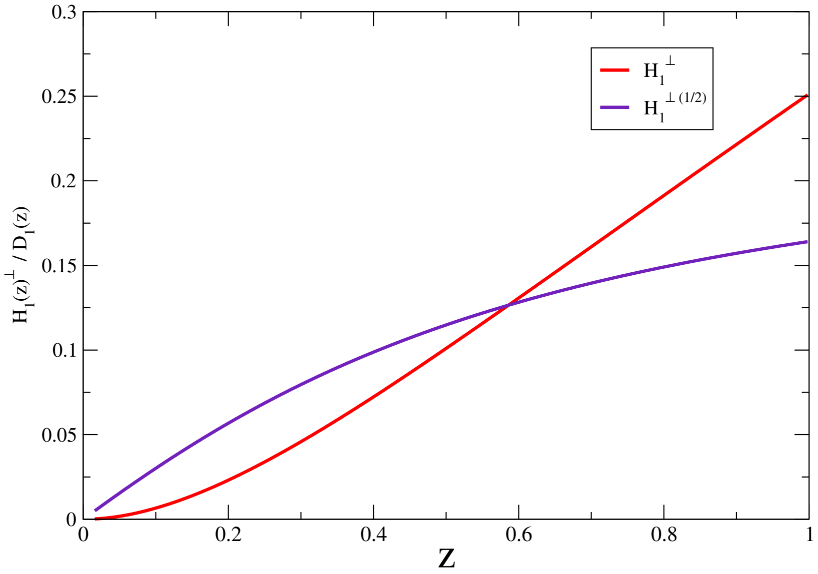
"pole contribution" Gribov-Lipatov Reciprocity 1974

Mulders et al. 1990s

Bacchetta, L.G., Goldstein, Mukherjee

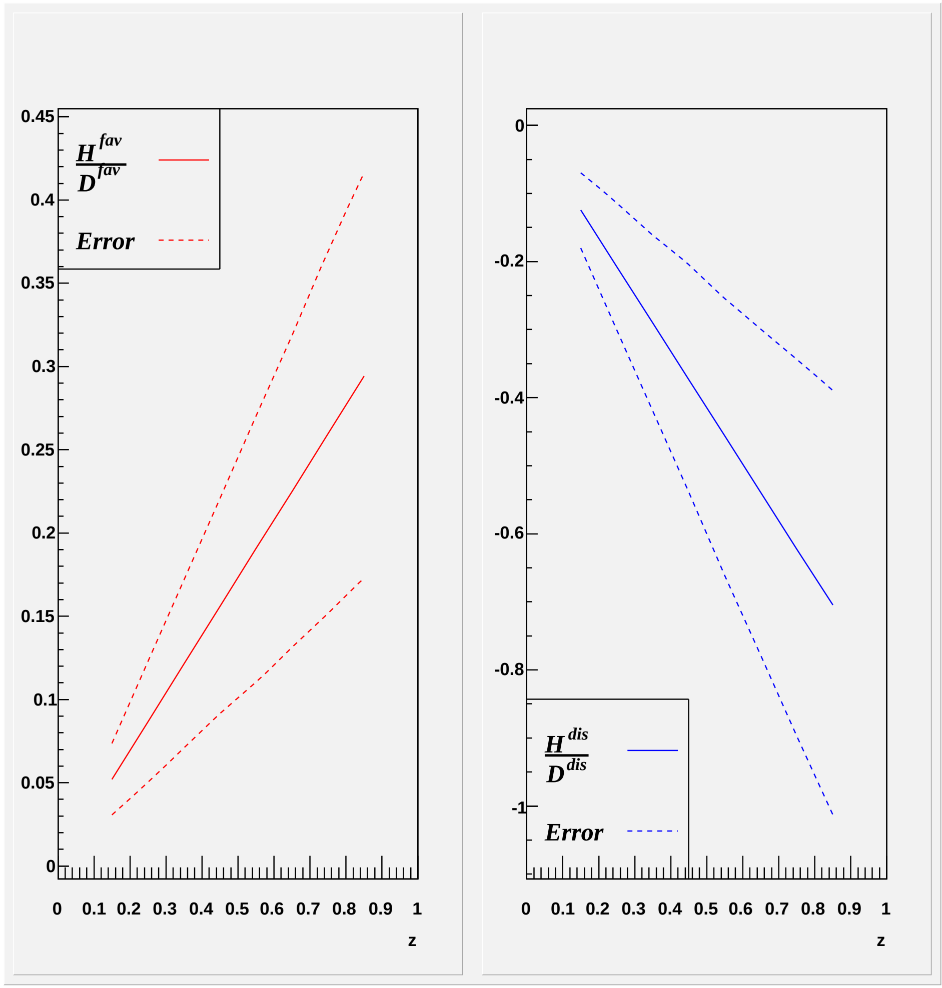
Re-analysis and Kaons

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

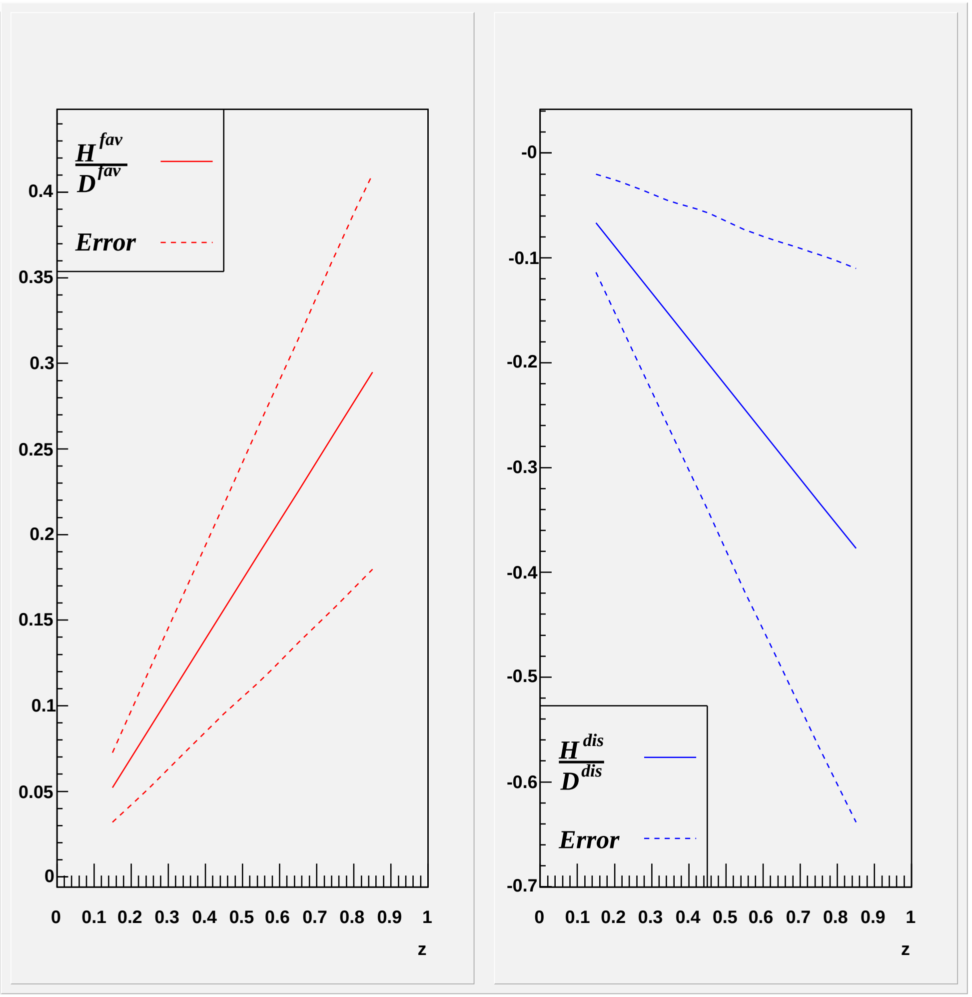


$\frac{H}{D}$ Plots

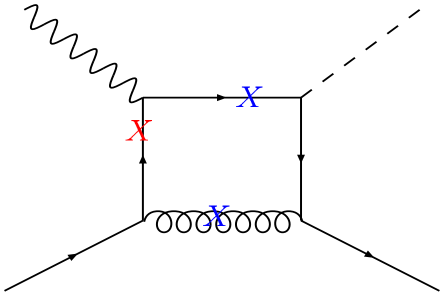
A_0



A_{12}



S-Channel Cut-COMO Proceedings 2006



$$H_1^{\perp}(z,k_\perp) \quad = \quad \mathcal{N}''\alpha_s \frac{M_\pi}{4z}(1-z)\frac{\mathcal{I}_1(z,P_\perp^2)+\mathcal{I}_2(z,P_\perp^2)}{\Lambda'(P_\perp^2)P_\perp^2}\,,$$

where

$$\mathcal{I}_1 \quad = \quad \pi(\mu - m(1-z))\frac{E_\pi + P\cos\theta}{P+E_\pi\cos\theta}\left[\ln\frac{(P+E_\pi\cos\theta)^2}{\mu^2} - \cos\theta\ln\frac{4P^2}{\mu^2}\right]$$

$$\mathcal{I}_2 \quad = \quad \pi\, z\, m\,\frac{P\sin^2\theta}{E_\pi - P\cos\theta}\ln\frac{4P^2}{\mu^2},$$

$P \equiv |\mathbf{P}_h|$ and $P_\perp^2 = k_\perp^2/z^2$. As in the case of the “gluonic pole” contribution, survives the limit that incoming quark mass $m_q \rightarrow\ 0$. Results depend the non-perturbative correlator mass μ χSB.

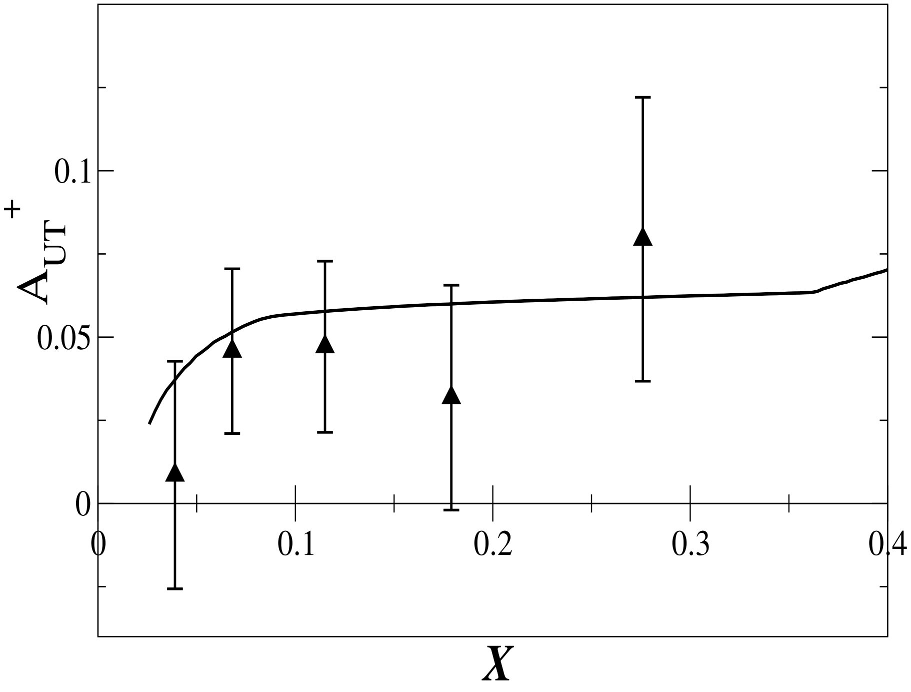
Collins Asymmetry

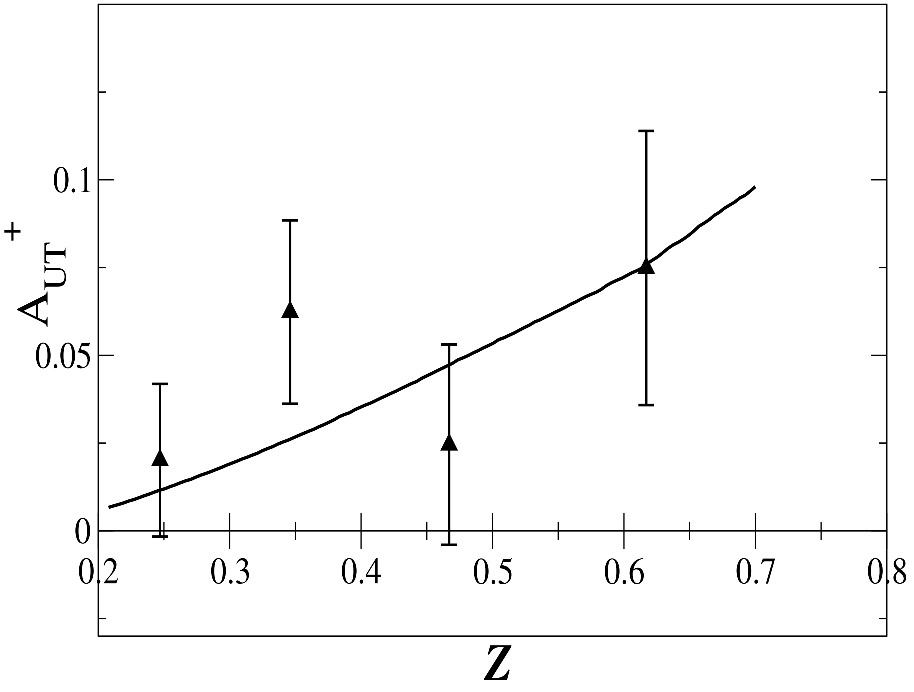
L.G., Goldstein, Oganessyan PRD 2003: updated For the HERMES kinematics

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

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

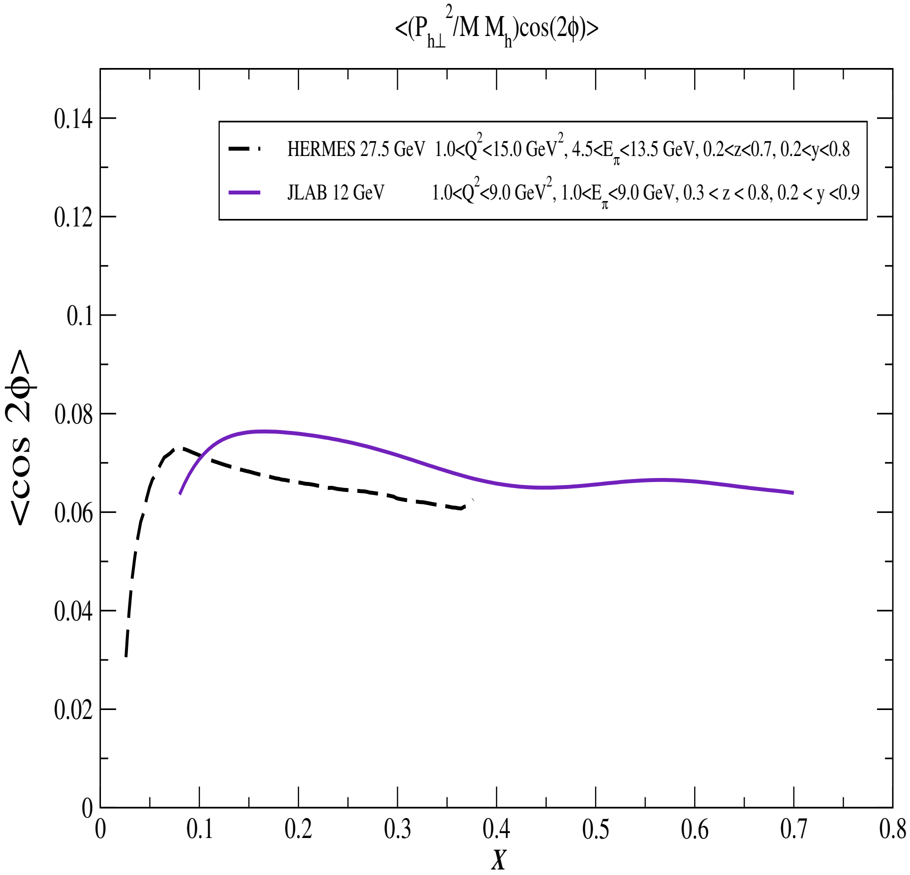
Data from A. Airapetian et al. PRL94,2005

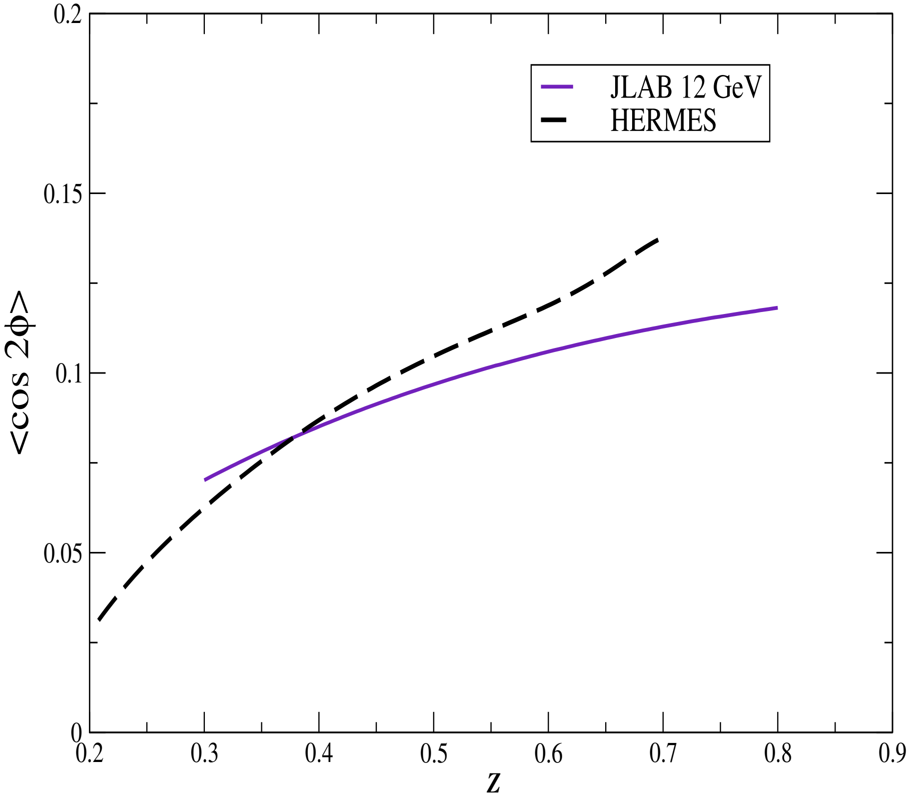




T-odd $\cos 2\phi$ asymmetry

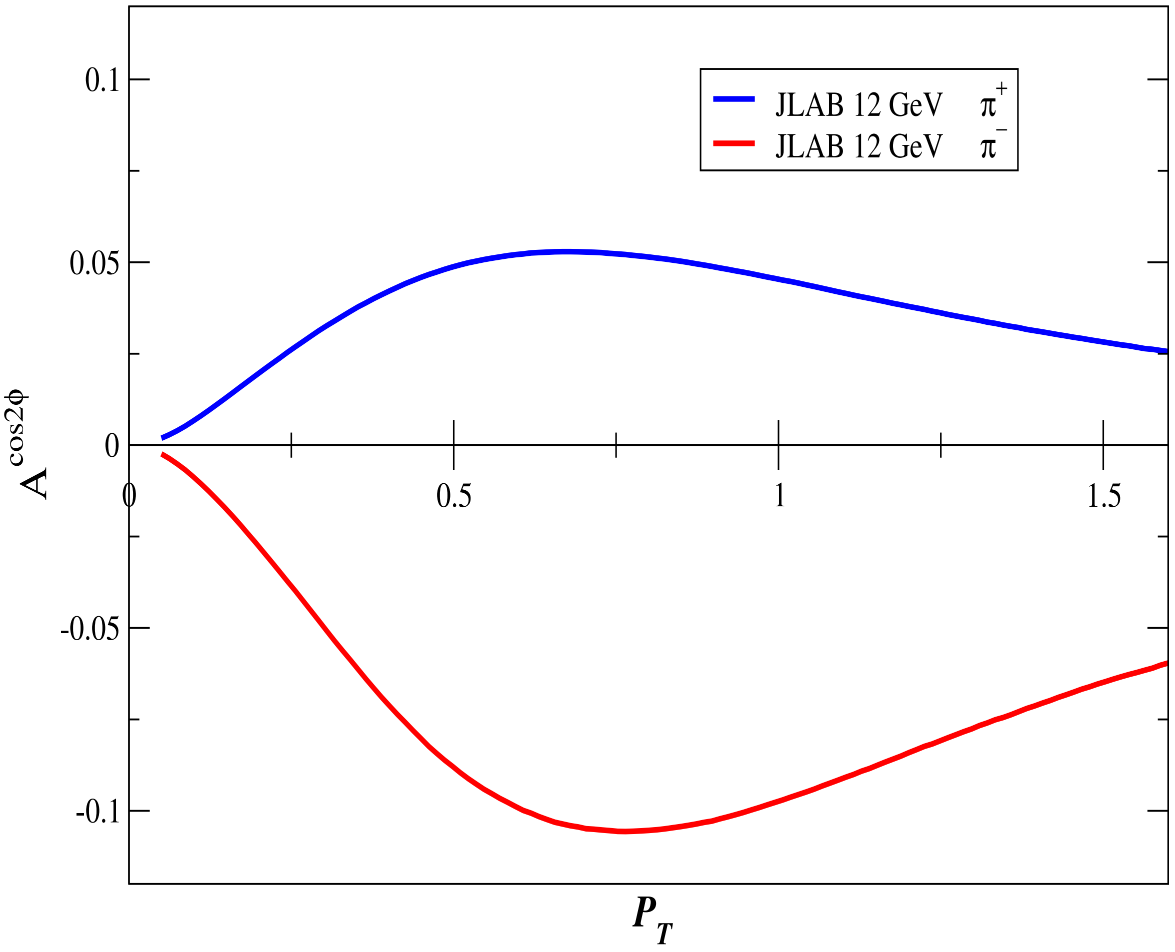
Transversity of quarks inside an unpolarized hadron, $\cos 2\phi$ SIDIS $\langle \frac{|P_{h\perp}^2|}{M M_h} \cos 2\phi \rangle_{UU}$



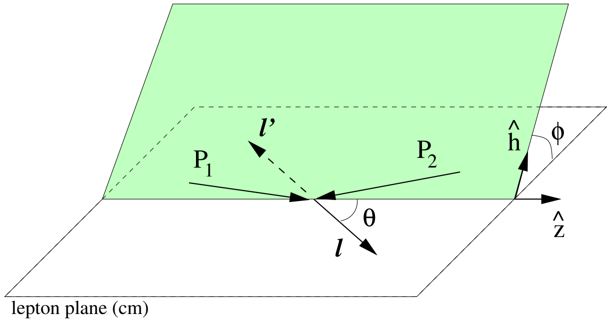


CLAS12 PAC 30-Avakian, Meziani. . . L.G. . .

Model assumption for dis-favored fragmentation $H_1^{\perp\ (d\to\pi^+)} = -H_1^{\perp\ (u\to\pi^+)}$



Boer-Mulders Effect in Unpolarized DRELL YAN $\cos 2\phi$



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

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

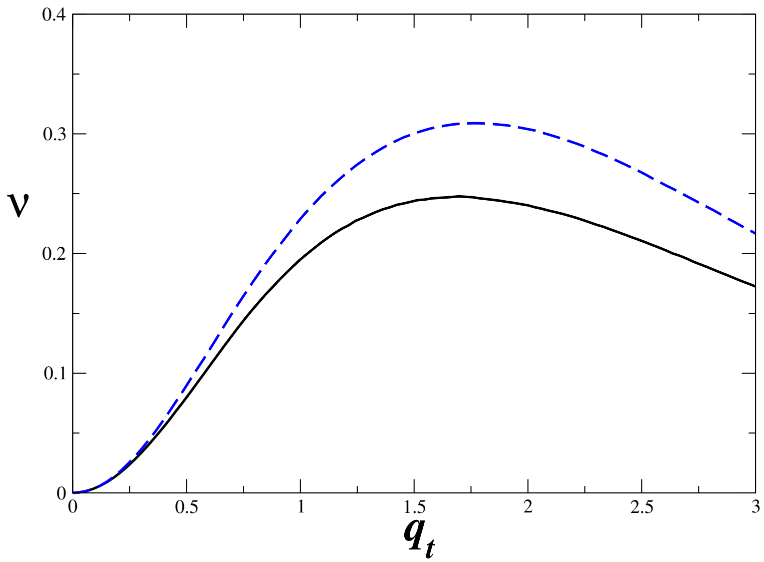
Boer PRD: 1999, Boer, Brodsky, Hwang PRD: 2003, L.G., Goldstein 2005

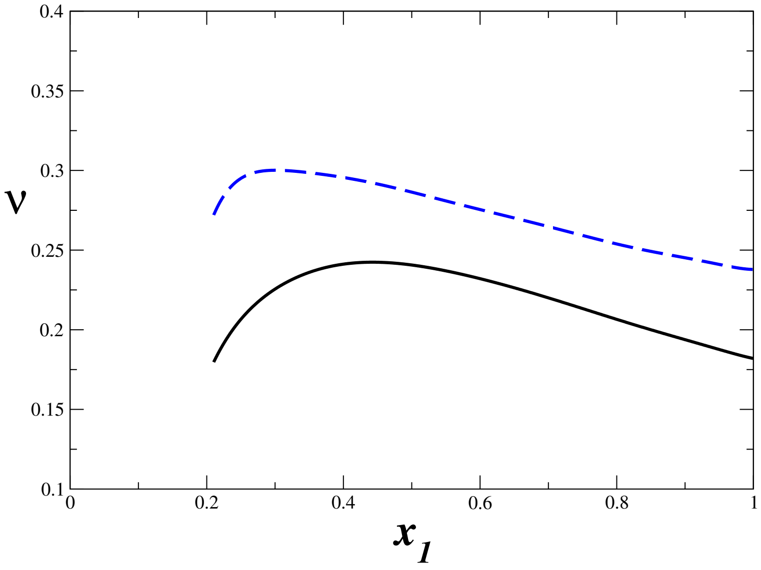
- Leading twist $\cos 2\phi$ azimuthal asymmetry depends on T-odd distribution $h_1^{\perp}$.

$$\nu_2 = \frac{2\sum_a e_a^2 \mathcal{F}\left[\mathcal{W}_2 \frac{h_1^{\perp}(x,\boldsymbol{k}_T)\bar{h}_1^{\perp}(\bar{x},\boldsymbol{p}_T)}{M_1 M_2}\right]}{\sum_a e_a^2 \mathcal{F}[f_1 \bar{f}_1]}$$

- Higher twist comes in Collins SoperPRD: 1977

$$\nu_4 = \frac{\frac{1}{Q^2}\sum_a e_a^2 \mathcal{F}\left[\mathcal{W}_4 f_1(x,\boldsymbol{k}_\perp)\bar{f}_1(\bar{x},\boldsymbol{p}_\perp)\right]}{\sum_a e_a^2 \mathcal{F}\left(f_1(x,\boldsymbol{k}_\perp)\bar{f}_1(\bar{x},\boldsymbol{p}_\perp)\right)}$$





Perform Convolution integral L.G., Goldstein

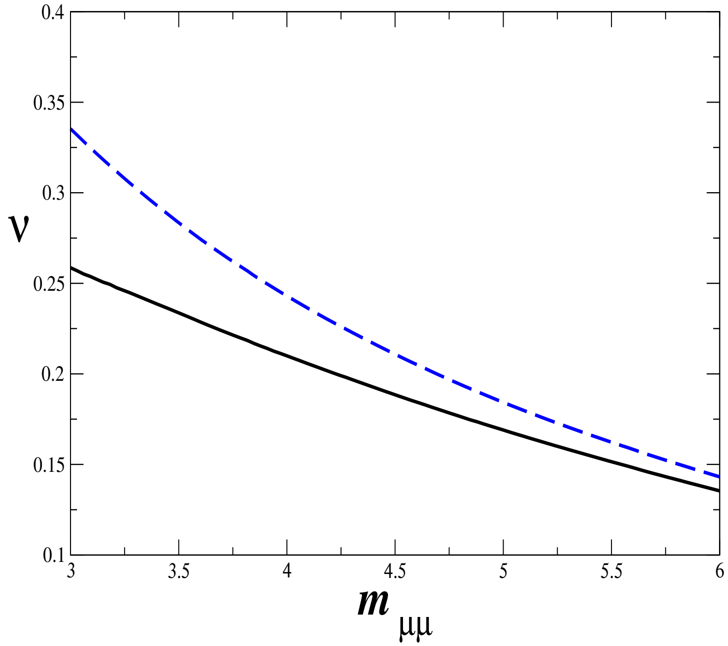
$s = 50\,\mathrm{GeV}^2$, $x = [0.2 - 1.0]$,

$q = [3.0 - 6.0]$ GeV, $\boldsymbol{q}_T = 0 - 2.0\,\mathrm{GeV}$

q_T^2/Q^2 corrections

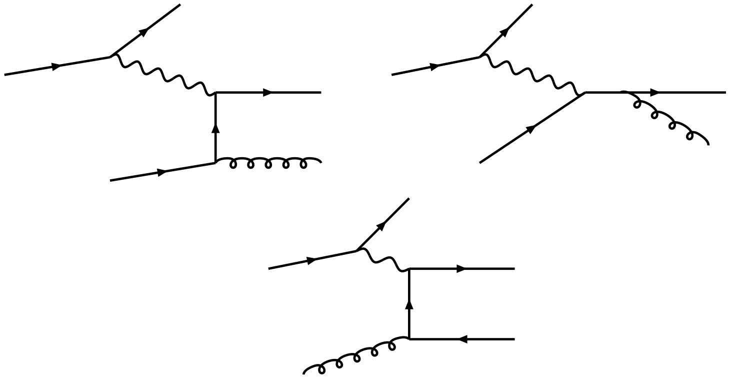
$x_1 x_2 = \frac{Q^2(1+q_T^2/Q^2)}{s}$

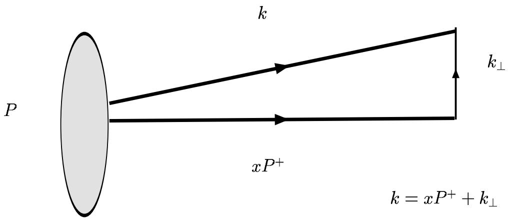
q_T/Q can be order 0.5



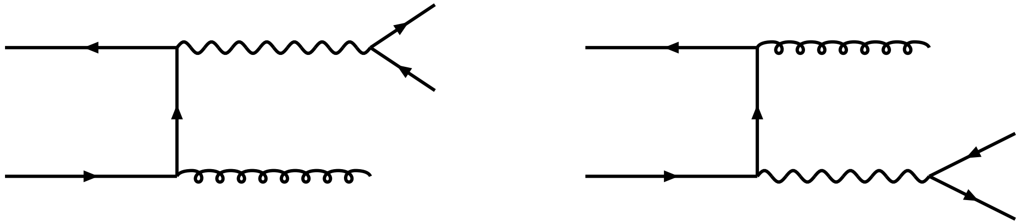
$\cos 2\phi$ JLAB, EIC, GSI, JPARC ...

- Georgi and Mendez 1975, gluon PQCD ".. gluon bremstrulang competes with convolution of $h_1^{\perp} \otimes H_1^{\perp}$
- Cahn Effect: Chay-Ellis PRD 1995,L.G., Goldstein, Oganessyan DIS03-proc 2003,Barone,Ma, PLB: 2006, Anselmino,Boglione,Prokudin, Turk Chay et al PRD: 95
- Qui Sterman Ji Yuan Vogelsang approach 2006

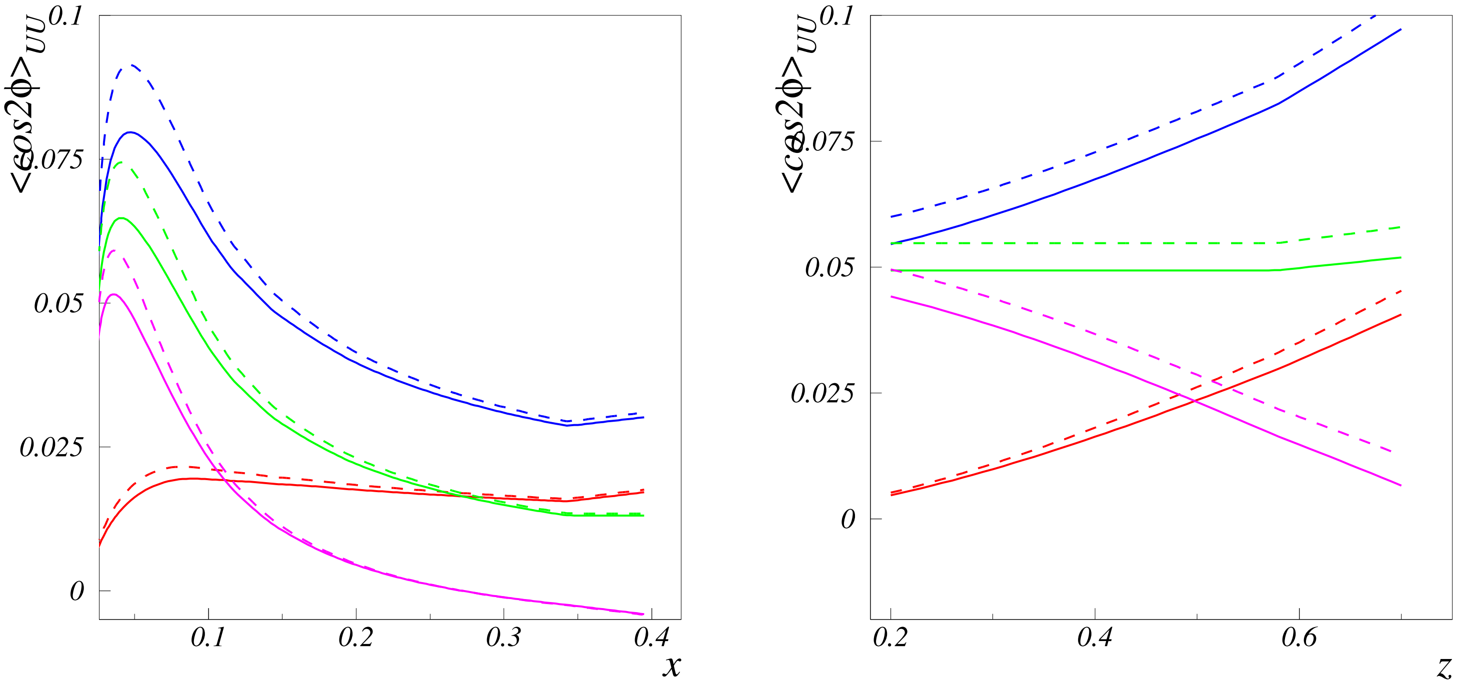




- Gluon bremstrulang Collins PRL: 1979 competes with convolution of $h_1^{\perp} \otimes \bar{h}_1^{\perp}$



$$\langle \cos 2\phi \rangle_{UU} \propto \frac{\frac{k_\perp^2}{Q^2} f_1(x) D_1(z) \pm h_1^{\perp(1)}(x) H_1^{\perp(1)}(z)}{f_1(x) D_1(z) + \frac{k_\perp^2}{Q^2} f_1(x) D_1(z)}.$$



SUMMARY

- Going beyond the collinear approximation in PQCD recent progress has been achieved characterizing transverse SSA and azimuthal asymmetries through "rescattering" mechanisms which generate T-odd, intrinsic transverse momentum, $k_\perp$, dependent *distribution and fragmentation* functions at leading twist
- Central to this understanding is the role that transversity properties of quarks and hadrons pocess terms of correlations between transverse momentum and transverse spin in QCD hard scattering

- The tranversity programs Belle, HERMES, RHIC, have uncovered large effects and near term Hall-A Transversity will start to check flavor structure of T-odd TMDs
- Future experiments to uncover the Boer Mulders function was approved at JLAB Hall B-CLAS12 proposal on $\cos 2\phi$. Will also be a check on the Collins function

⋆ Azimuthal asymmetries in Drell Yan and SSA can be measured at GSI-PAX, JPARC as well

⋆ Transverse spin effects are more than h_1