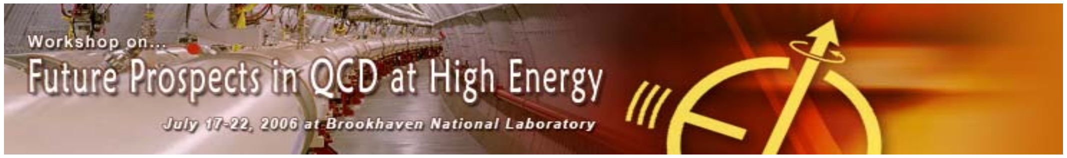
"Transverse Spin Effects in SIDIS and Drell Yan"

Leonard Gamberg*

Division of Science, Penn State Berks

Workshop on Future Prospects in QCD at High Energy



- Remarks Transverse Spin and Azimuthal Asymmetries in QCD
- ⋆ Reaction Mechanisms: Colinear-limit ETQS-Twist Three, Beyond Co-lineararity BHS-FSI Twist Two
- ⋆ Unintegrated PDF and FFs-ISI/FSI: "T-odd" TMDs Distribution and Fragmentation Functions: Correlations btwn intrinsic $k_\perp$, transverse spin S_T
- ⋆ TSSA and Estimates of the Collins and Sivers Functions
- ⋆ Double T-odd $\cos 2\phi$ asymmetry in SIDIS & DRELL-YAN
- Conclusions

* G. R. Goldstein (Tufts) K.A. Oganessyan *NYC*, and D.S. Hwang (Sejong) Andreas Metz, Marc Schlegel (Bochum)

Transverse SSA (TSSA) and AZIMUTHAL ASYMMETRIES (AA)

⋆ Co-linear approximation of QCD PREDICTS
vanishingly small TSSA at large scales and leading order α_s

- Generically,

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

⋆ Requires *helicity flip* as well as relative phase btwn helicity amps

- Massless QCD conserves helicity & Born amplitudes are real!

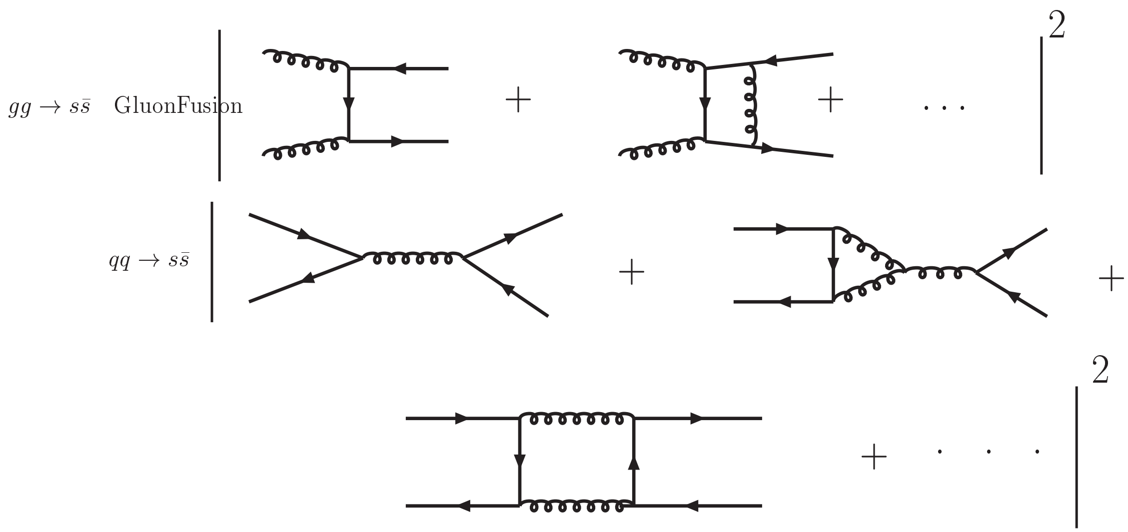
⋆ Incorporating Interference btwn loops-tree level Kane, Repko, PRL:1978
demonstrate $A_N \sim m_q \alpha_s / Q$ within PQCD

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

PQCD contributions calculated: Dharmartna & Goldstein PRD 1990

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

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

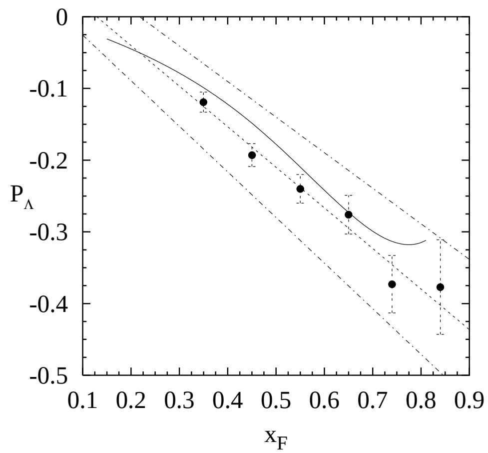


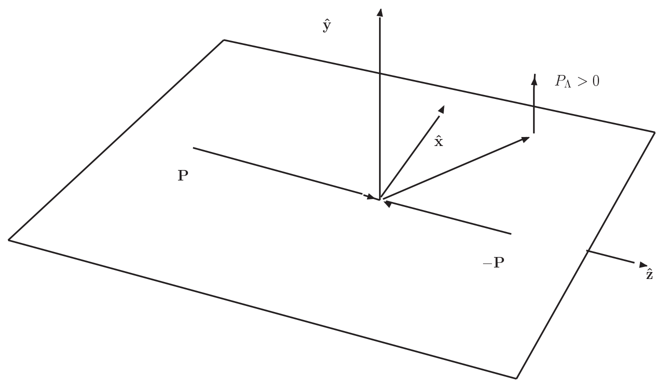
- Polarization $P_{\Lambda} \sim m_q \alpha_s / Q$ is twist 3 & small $\approx 5\%$ as predicted on general grounds, m_q is the strange quark mass

- Experiment *glaringly at odd with this result*

P_Λ in p-p scattering from Fermi Lab

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



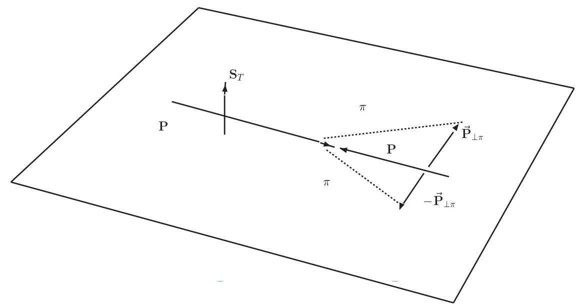


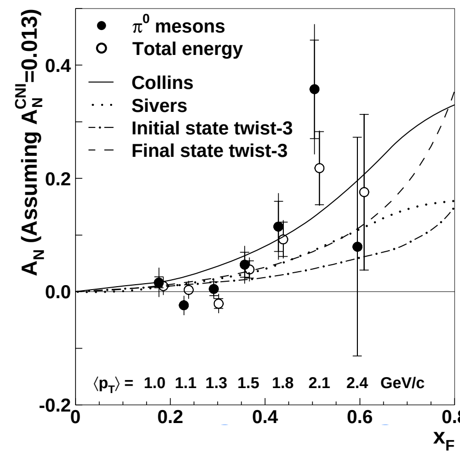
Heller,...,Bunce PRL:1983 PRL: 1983: Up-down asymmetry depicted for Λ production in p-p COM-frame.

LARGE TSSAS OBSERVED: E704-Fermi Lab, STAR & PHENIX $p^{\uparrow}p \to \pi \;\; X$

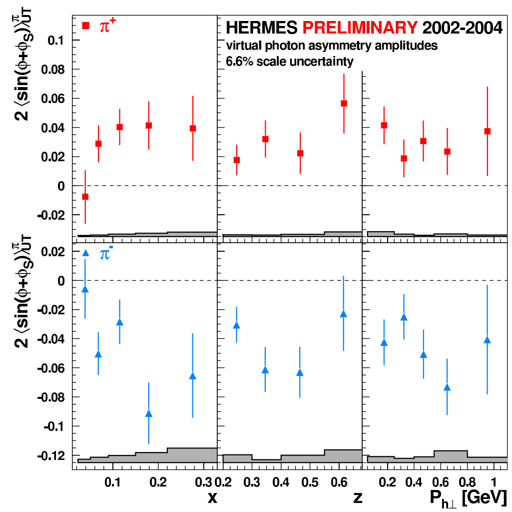
L-R asymmetry of π production and A_N for π_0 production at STAR : PRL 2004

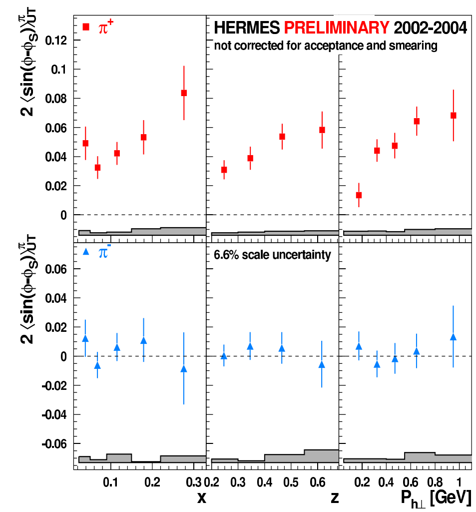
$$A_N = \frac{d\sigma^{p^{\uparrow}p\to\pi \;\; X} - d\sigma^{p^{\downarrow}p\to\pi \;\; X}}{d\sigma^{p^{\uparrow}p\to\pi \;\; X} + d\sigma^{p^{\downarrow}p\to\pi \;\; X}}$$



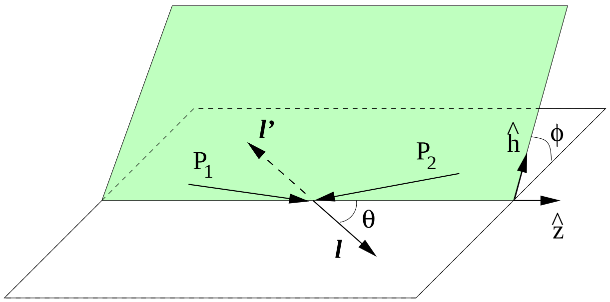


HERMES $e \; p^{\uparrow} \to \pi \;\; X$





Azimuthal Asymmetry in Unpolarized DRELL YAN $\cos 2\phi$



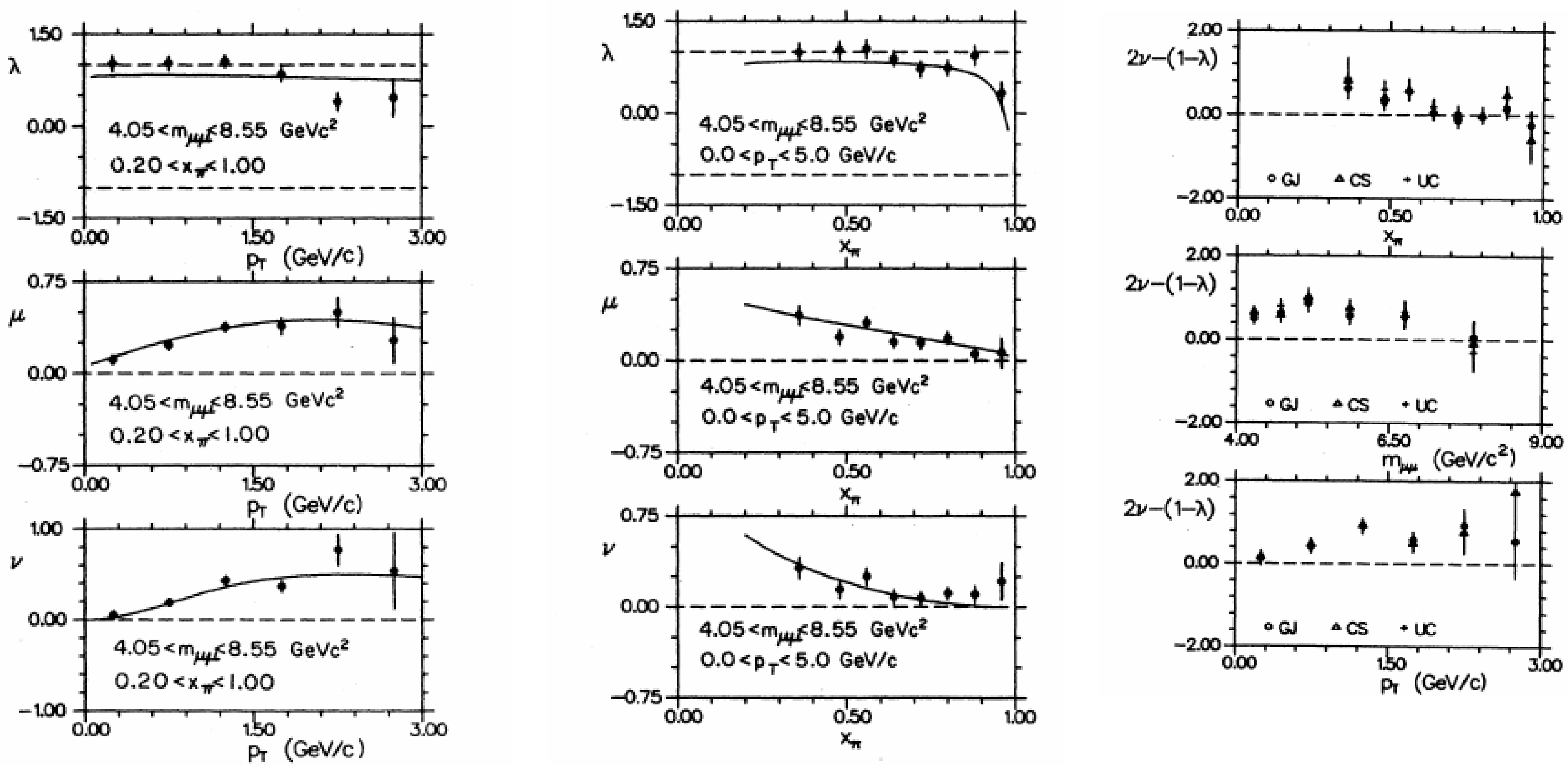
$$\pi^- + p \rightarrow \mu^+ + \mu^- + X$$

At first sight reaction appears to be independent transverse spin correlations. However, inability of QCD-Parton Model to account for AA maybe explained by transverse spin correlations of quarks and transverse momentum of photon

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

λ, μ, ν, **depend on** $s, x, m^2_{\mu\mu}, q_T$: **QCD-parton Model NNLO predict Lam-Tung relation (Mirkes Ohnemus, PRD 1995),** $1 - \lambda - 2\nu = 0$

Unexpectedly large $\cos 2\phi$ AA E615,Conway et al. 1986, NA10, ZPC, 1986 compared parton-model: violating Lam-Tung relation



Lam-Tung Relationship Violated

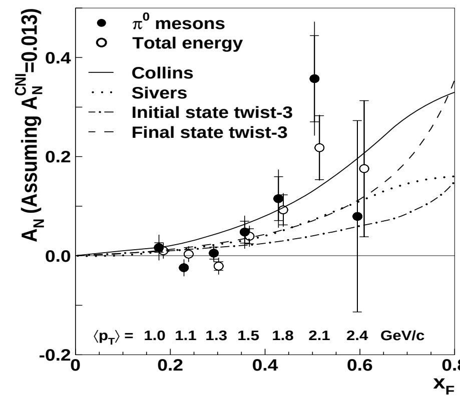
ETQS-Twist Three Mechanism @ Lg $P_T > \Lambda_{qcd}$

Can describe TSSAs $p\,p^{\perp} \to \pi X$

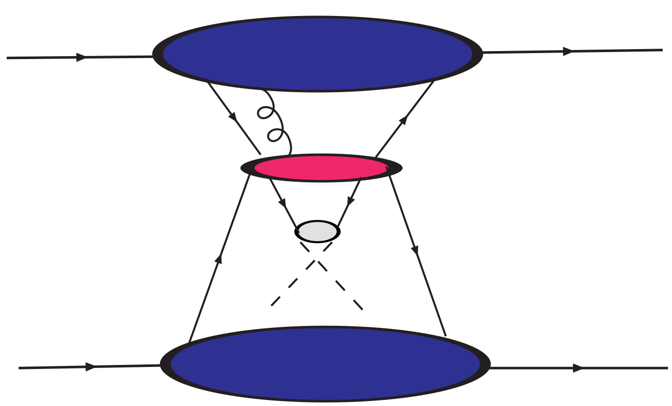
A_N twist three, yet phases generated in co-linear QCD from gluonic and fermionic poles in propagator of hard parton subprocess

Efremov & Teryaev :PLB 1982

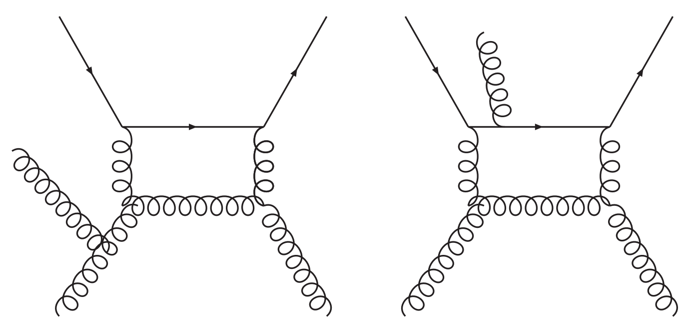
$$\frac{1}{x+s \pm i\epsilon} = P\frac{1}{x-s} \mp i\pi\delta(x-s)$$



- Factorized co-linear QCD Qiu & Sterman :PLB 1991, 1999 & Koike & Kanazawa:PLB 2000 at
  Get helicity flips and phases, $m_q \to\sim M_H$ and $\alpha_s \to \sqrt{\alpha_s}$



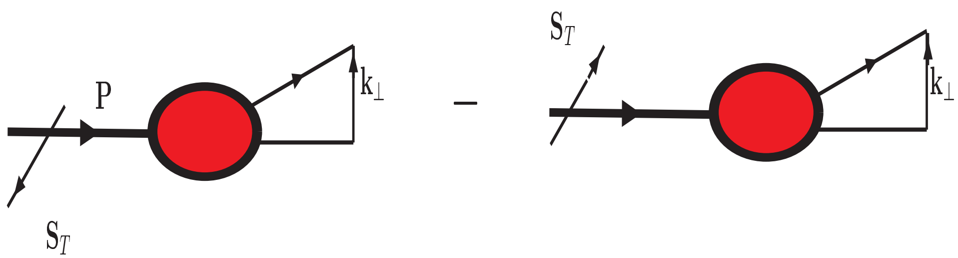
$\Rightarrow$

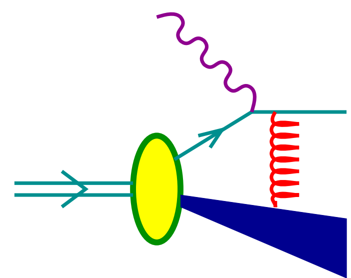


$\boldsymbol{p}_T \sim k_\perp \sim \Lambda_{\rm qcd}$ "Naive-T-Odd" Correlations thru TMDs

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

- TSSA indicative "T-odd" correlation of *transverse* spin and momenta
  Sivers: PRD 1990 Correlation accounts for left-right TSSA in $P\,P^\perp \to \pi\,X$





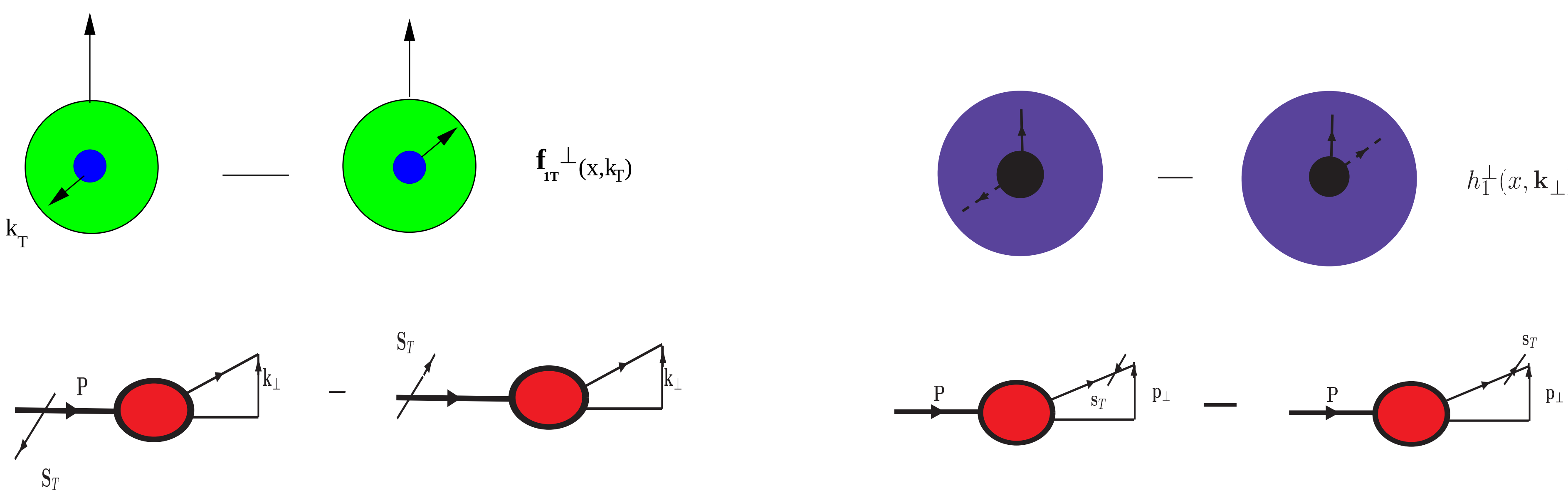
- In SIDIS with transverse polarized nucleon target $e\;p^\perp \to \pi X$
  $i\boldsymbol{S}_T \cdot (\boldsymbol{P} \times \boldsymbol{k}_\perp) \to f_{1T}^\perp(x, \boldsymbol{k}_\perp)$ production
  Brodsky, Hwang, and Schmidt PLB: 2002 FSI produce necessary phase for TSSAs-*Leading Twist*
  Ji & Yuan PLB: 2002 -Sivers fnct. FSI emerge from Color Gauge-links-spectator approx.

- Collins NPB 1993 "T-odd" correlation of transversely polarized fragmenting quark:
  TSSA in lepto-production $is_T \cdot (\boldsymbol{p} \times \boldsymbol{P}_{h\perp}) \to H_1^\perp(z, \boldsymbol{p}_\perp)$
  s_T spin of fragmenting quark, $\boldsymbol{p}$ quark momentum and $\boldsymbol{P}_{h\perp}$ transverse momentum produced pion

(!) Also "T-odd" Correlation of Transversely polarized quark *in an unpolarized Nucleon* -Boer Mulders Effect

Boer and Mulders PRD 1998 "T-odd" correlation of transversely polarized *quark spin* with it's intrinsic $\boldsymbol{k}_\perp$ $is_T \cdot (\boldsymbol{k} \times \boldsymbol{P}) \to h_1^\perp(x, \boldsymbol{k}_\perp)$-Of What Intrest is This?!
May drive $\cos 2\phi$-AA in unpolarized lepto-production $e\,P \to e'\,\pi\,X$ and Drell Yan $\pi^- + p \to \mu^+ + \mu^- + X$ or $\bar{p} + p \to \mu^- \mu^+ + X$ (latter is cleaner, no Fragmentation)

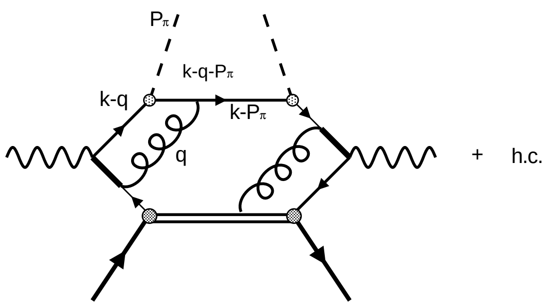
s_T spin of fragmenting quark, $\boldsymbol{k}$ quark momentum and $\boldsymbol{P}$ proton momentum

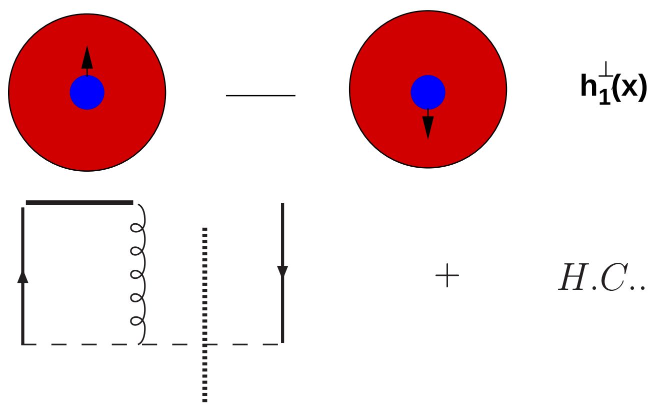


FSI Mechanism can Generate Boer-Mulders-$h_1^\perp$

Goldstein, L.G.–ICHEP-proc-hep-ph/0209085 (2002), L.G., Goldstein, Oganessyan PRD 2003

- $h_1^\perp$ "Naturally" defined from Color G.I. TMD: Convoluted with $H_1^\perp$ enters $\cos 2\phi$ in SIDIS
- $h_1^\perp$ Convoluted with $\bar{h}_1^\perp$ enters $\cos 2\phi$ in Unpolarized Drell Yan w/ sensitivity to $\boldsymbol{q}_T$
- "Eikonal Feynman rules" to calculate Collins Soper: NPB: 1982



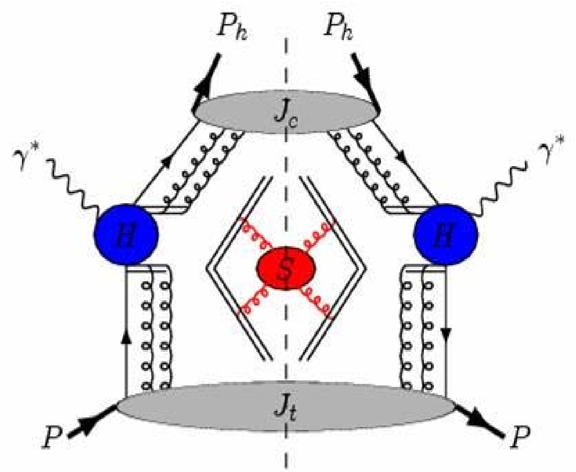


$$\Phi^{[\sigma^{\perp +}\gamma_5]}_{[h_1^\perp]}(x,k_\perp) = \frac{1}{2}\int dp^- \mathrm{Tr}\left(i\sigma^{+\perp}\gamma_5 \Phi\right) = \frac{\varepsilon_{+-\perp j}k_{\perp j}}{M} h_1^\perp(x,k_\perp)$$

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

Factorization Demonstrated For TMD- PDF and FF and Hard and Soft Parts

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



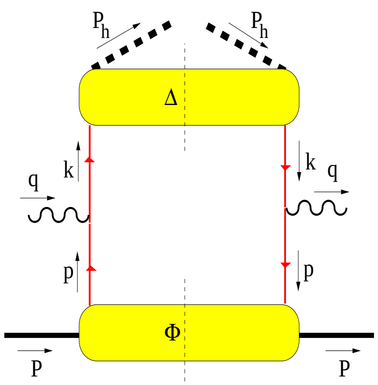
Universality & Factorization "Maximally" Correlated Collins and Metz: PRL 2005

Beyond Co-linear QCD: T-Odd Correlations

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, Levelt & Mulders, Mulders & Tangerman, NPB: 1994, 1996

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



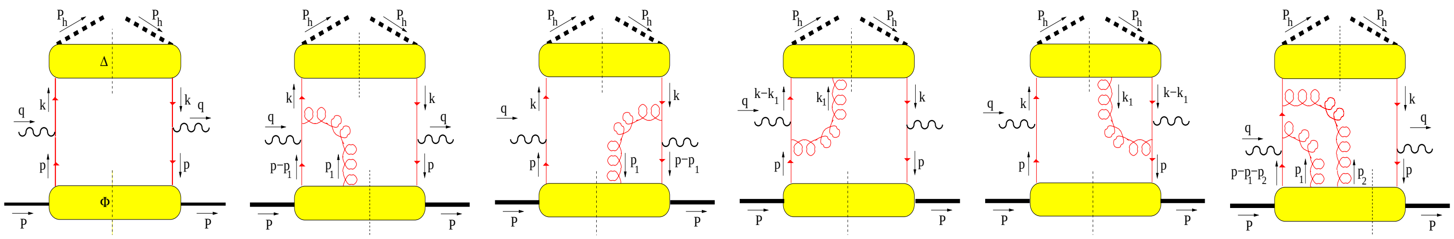
Hadronic Tensor

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

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

- 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 Φ and fragmentation Δ operators

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

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

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

Provide source of T-Odd Contributions to TSSA and AA

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

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

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

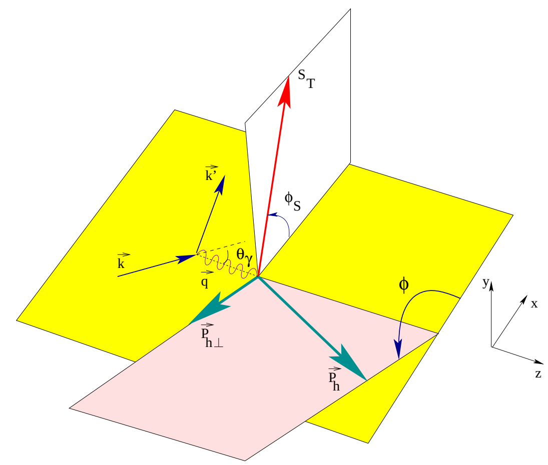
SIDIS cross section

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

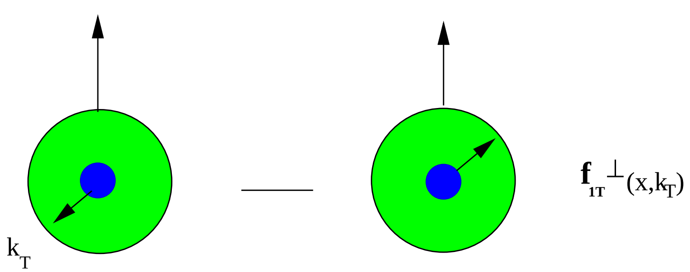
SIDIS-TSSAS Leading Twist-HERMES-COMPASS-JLAB-*EIC*

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

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



- Sivers PRD: 1990, Anselmino & Murgia PLB: 1995 ...

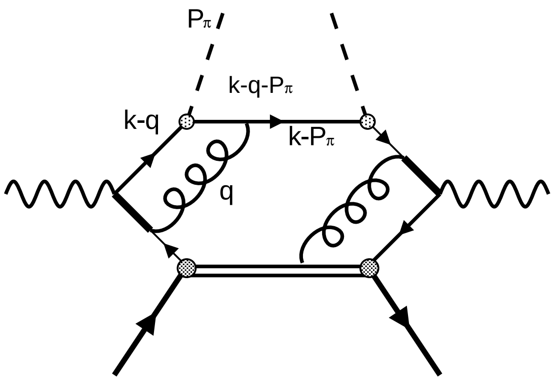


$$\langle \frac{|P_{h\perp}|}{M}\sin(\phi-\phi_S)\rangle_{UT} \quad = \quad |\boldsymbol{S}_T|\frac{(1+(1-y)^2)\sum_q e_q^2 f_{1T}^{\perp(1)}(x) z D_1^q(z)}{(1+(1-y)^2)\sum_q e_q^2 f_1(x) D_1(z)},$$

- Probes the probability for a transversely polarized target, pions are produced asymmetrically about pion production plane

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

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



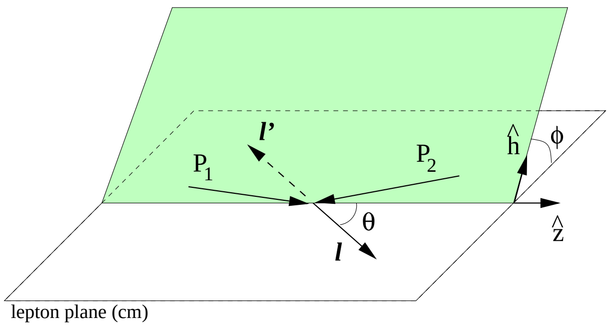
$$\frac{\int d^2 P_{h\perp} \frac{|P_{h\perp}^2|}{M M_h} \cos 2\phi \, d\sigma}{\int d^2 P_{h\perp} \, d\sigma} = \langle \frac{|P_{h\perp}^2|}{M M_h} \cos 2\phi \rangle_{UU} = \frac{8(1-y) \sum_q e_q^2 h_1^{\perp(1)}(x,Q^2) z^2 H_1^{\perp(1)q}(z,Q^2)}{(1+(1-y)^2) \sum_q e_q^2 f_1^q(x,Q^2) D_1^q(z,Q^2)}$$

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

Leading Twist Contribution from T-Odd D. Boer, P. Mulders, PRD: 1998

Boer-Mulders Effect in Unpolarized DRELL YAN as well as TSSAs

(GSI & JPARC)



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

SSAs& T-odd Contribution in Drell Yan (GSI & JPARC)

$$\frac{d\Delta\sigma^{\uparrow}}{d\Omega dx_1 dx_2 d\boldsymbol{q}_T} \propto \sum_a e_f^2 \, |\boldsymbol{S}_{2_T}| \Big\{ -B(y)\ \sin(\phi + \phi_{S_2})\ F\left[\hat{\boldsymbol{h}} \cdot \boldsymbol{p}_{1_T} \frac{\bar{h}_1^{\perp\, a}\, h_1^a}{M_1}\right]$$

$$+ A(y)\ \sin(\phi - \phi_{S_2})\ F\left[\hat{\boldsymbol{h}} \cdot \boldsymbol{p}_{2_T} \frac{\bar{f}_1^{a}\, f_{1T}^{\perp\, a}}{M_2}\right]\ \ldots\Big\}\ ,$$

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

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

⋆ Spectator framework used in models of BHS and Ji-Yuan assumes point-like nucleon-quark-diquark vertex, leads to logarithmically divergent, asymmetries

Goldstein, L.G., ICHEP 2002; hep-ph/0209085,

L.G., Goldstein, Oganessyan PRD 2003; Boer, Brodsky, Hwang, PRD: 2003(Drell-Yan)

$$\begin{aligned} h_1^{\perp(s)}(x, k_\perp) &= f_{1T}^{\perp(s)}(x, k_\perp) \\ &= \alpha_s N_s \frac{(1-x)M(m+xM)}{k_\perp^2 \Lambda(k_\perp^2)} \ln \frac{\Lambda(k_\perp^2)}{\Lambda(0)} \end{aligned}$$

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

- 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 $k_\perp^2$,

L.G., Goldstein, Oganessyan, PRD 67 (2003)

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

where $b \equiv \frac{1}{\langle k_\perp^2\rangle}$

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

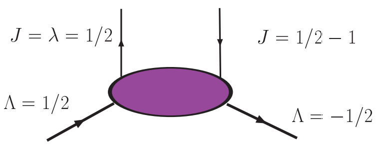
$$h_1^\perp(x,k_\perp) \quad = \quad \alpha_s\mathcal{N}_s\frac{M(m+xM)(1-x)}{k_\perp^2\Lambda(k_\perp^2)}\mathcal{R}(k_\perp^2,x)$$

with

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

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

GPDs and correlations of transverse spin and intrinsic $k_\perp$



- Intriguing connection of Sivers effect/function $f_{1T}^{\perp(q)} \leftrightarrow -\kappa^q$ with anomolus magnetic moment of quark-q through the impact parameter space representation of the spin-flip, chirally-even GPD $\mathcal{E}(x, \boldsymbol{b}_\perp)$: serves to fix sign of Sivers function
- As well $\kappa_T^q \leftrightarrow h_1^{\perp q}$ through comb. $\kappa_T^q = -\int dx(2\bar{H}_T(x,0,0) + E_T(x,0,0))$ (chirally odd transversity GPDs) where κ_T is the transverse spin-flavor dipole moment in an unpolarized proton
- Yeilds *transverse distortion* in impact parameter space of transversly polarized quarks in an unpolarized nucleon Burkardt PRD 2005
- Picture tells us in what direction and by how much the av. position of quarks w/ spin pol. in $\hat{\boldsymbol{x}}$ are shifted in the $\hat{\boldsymbol{y}}$ direction in an unpolarized target relative to their center of momentum.

⋆ This result implies that the up and down quark Boer Mulders function are same sign. Confirms Lg N_C arguments of Pobylitsa hep-ph/0301236. Implications on $\cos 2\phi$ phenomenology in SIDIS & Drell Yan

- Lattice QCDSF/UKQCD, Hägler et al... calculations of matrix elements on the lattice

Deformed quark densities and spin asymmetries

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

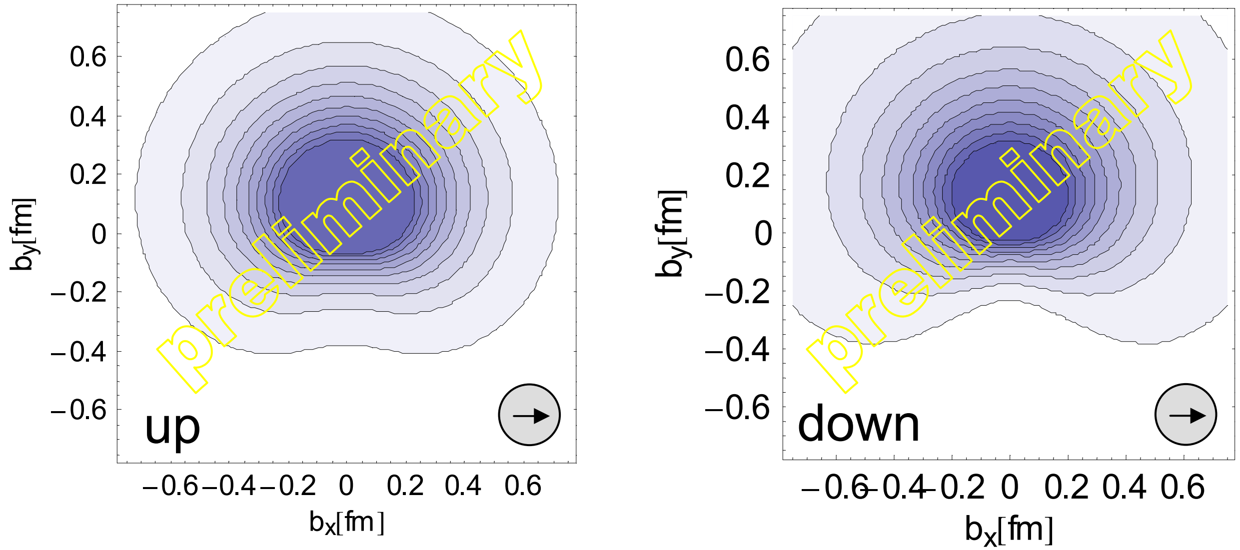
$$f_{1Tq}^{\perp}(x,p_{\perp}) \sim -\int dx E_q(x,0,0) = -B_{10,q}(0) = -\kappa_q$$

Burkardt PRD 2005

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

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

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

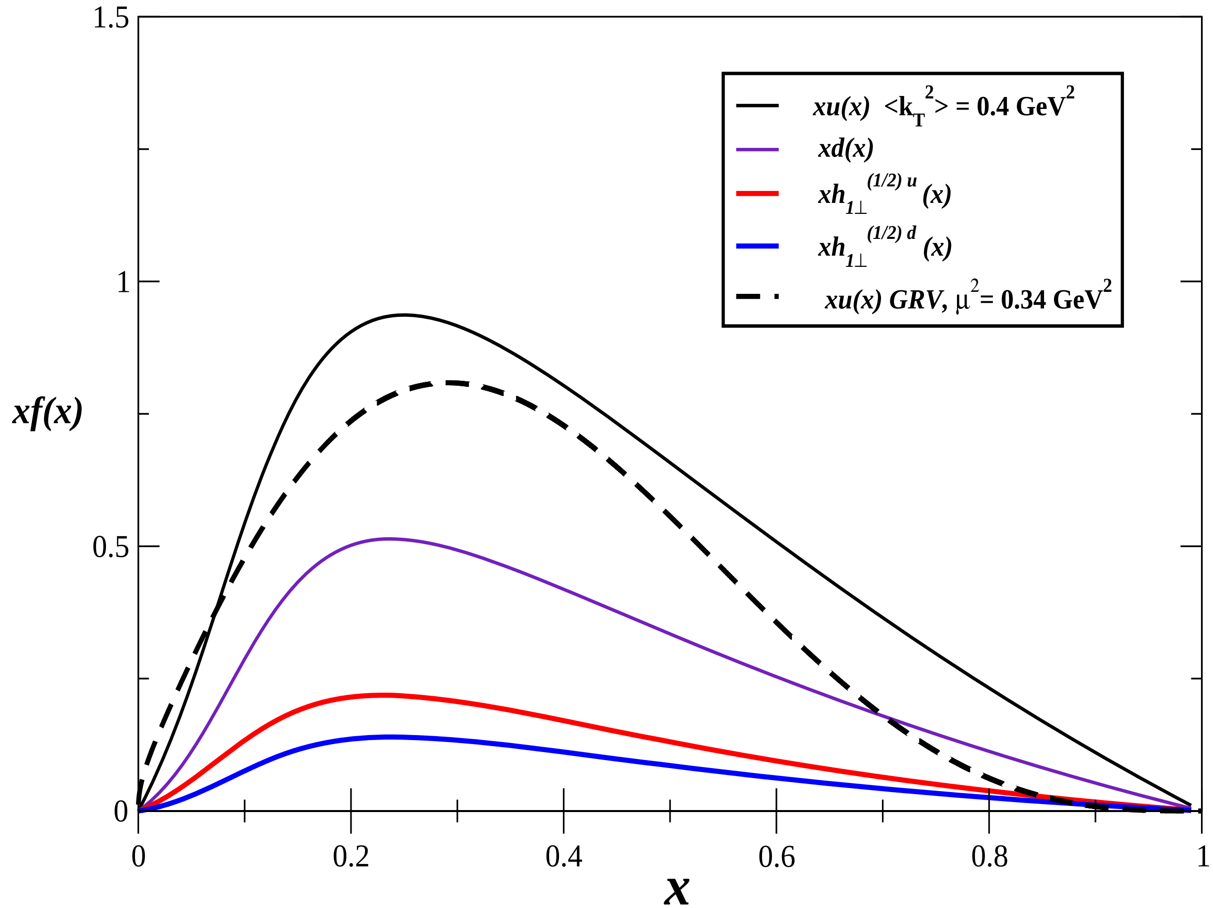


could imply to sizeable Boer-Mulders-effect

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

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

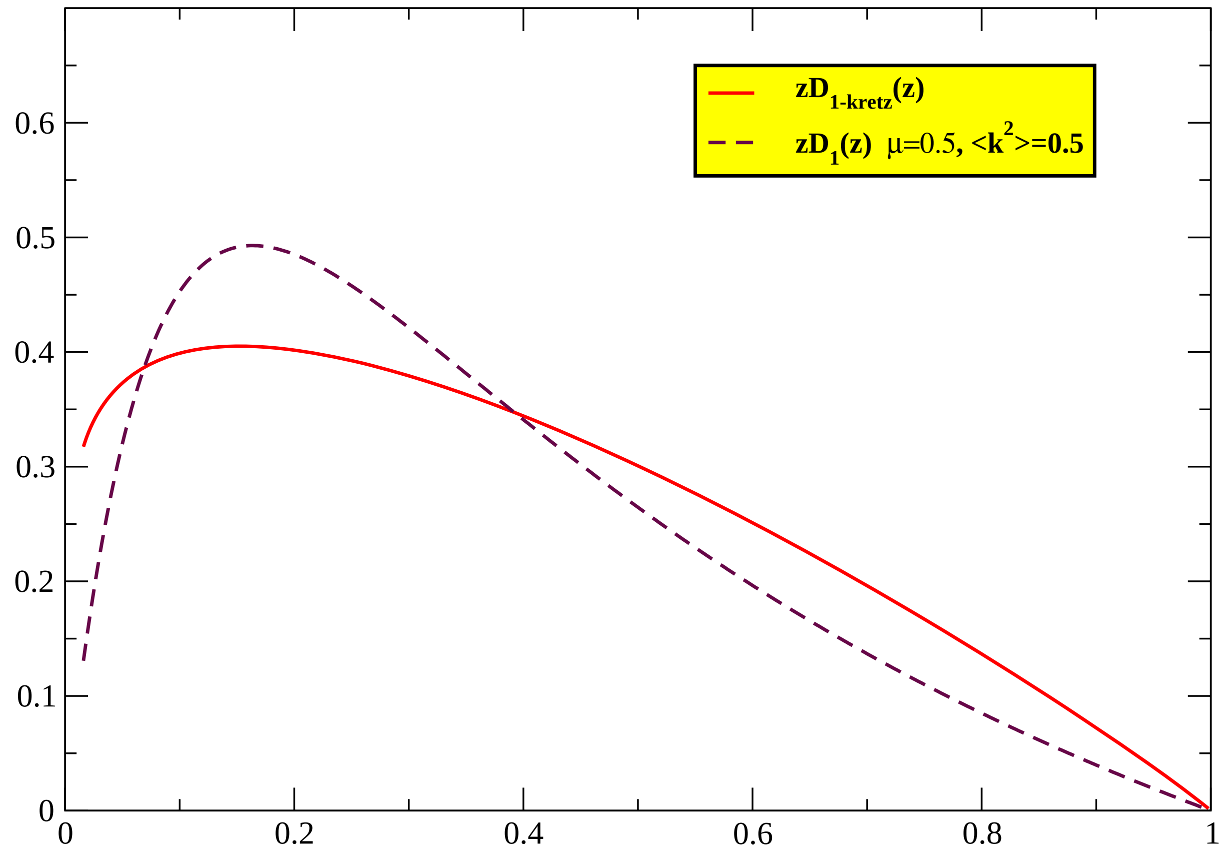
- ⋆ Valence Normalization,
  $\int_0^1 u(x) = 2$, $\int_0^1 d(x) = 1$
- Black curve- $xu(x)$
- Dashed curve - $xu(x)$ GRV
- Red/Blue curve $xh_1^{\perp(1/2)(u,d)}$
- axial vector diquark coupling
  Jakob, Mulders, Rodrigues
  NPB:1997,
  $\gamma_5(\gamma^\mu + P^\mu/M)$



Pion Fragmentation Function

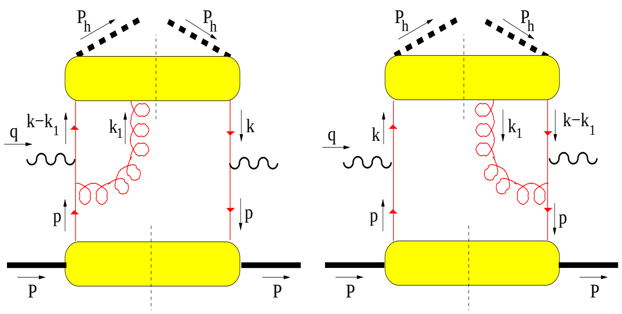
$$D_1(z) \quad = \quad \mathcal{N}'\frac{1}{z}\frac{(1-z)}{z}\Big\{\frac{m^2-\Lambda'(0)}{\Lambda'(0)} - \left[2b'\left(m^2-\Lambda'(0)\right)-1\right]e^{2b'\Lambda'(0)}\Gamma(0,2b'\Lambda'(0))\Big\},$$

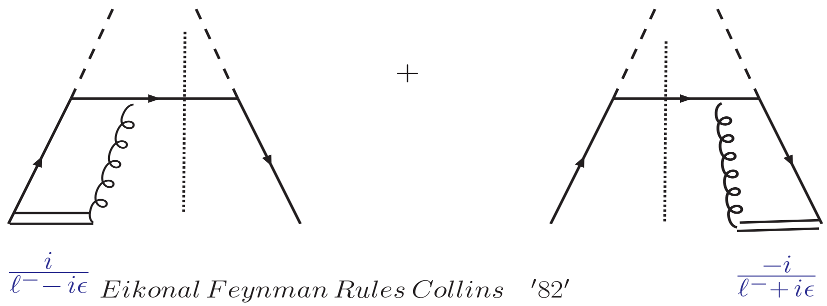
which, multiplied by z at $< k_\perp^2 >= (0.5)^2$ GeV^2 and $\mu = m$, estimates the distribution of Kretzer, PRD: 2000



Gauge Link-Pole Contribution to T-Odd Collins Function

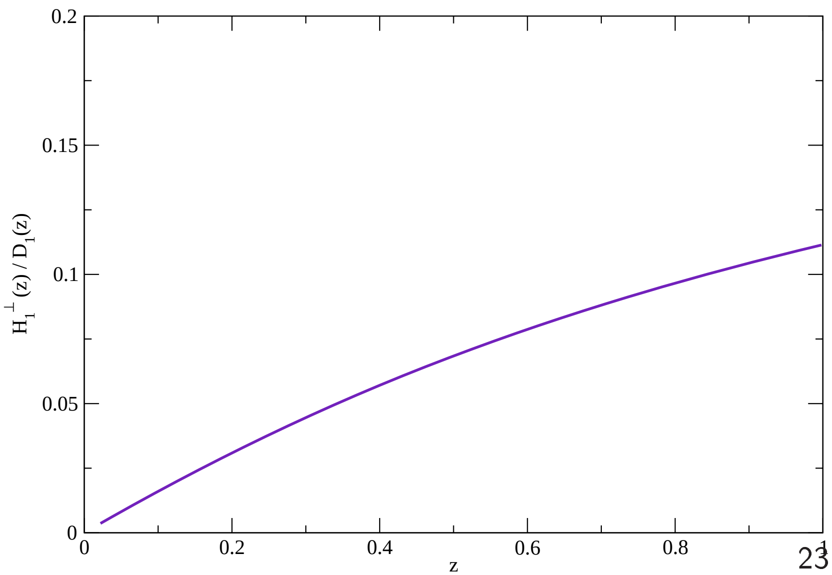
L.G.,Goldstein,Oganessyan PRD68,2003 $\Delta^{[\sigma^{\perp -}\gamma_5]}(z,k_\perp) = \frac{1}{4z}\int dk^+ Tr(\gamma^-\gamma^\perp\gamma_5\Delta)|_{k^-=P_\pi^-/z}$





Motivation:color gauge .inv frag. correlator
"pole contribution" Gribov-Lipatov Reciprocity 1974
Mulders et al. 1990s

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

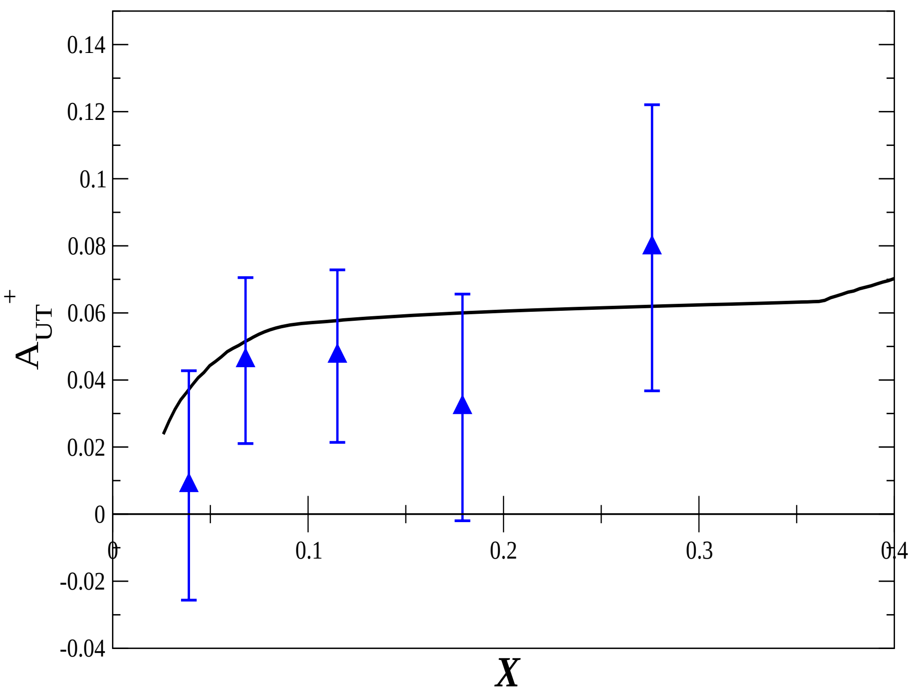


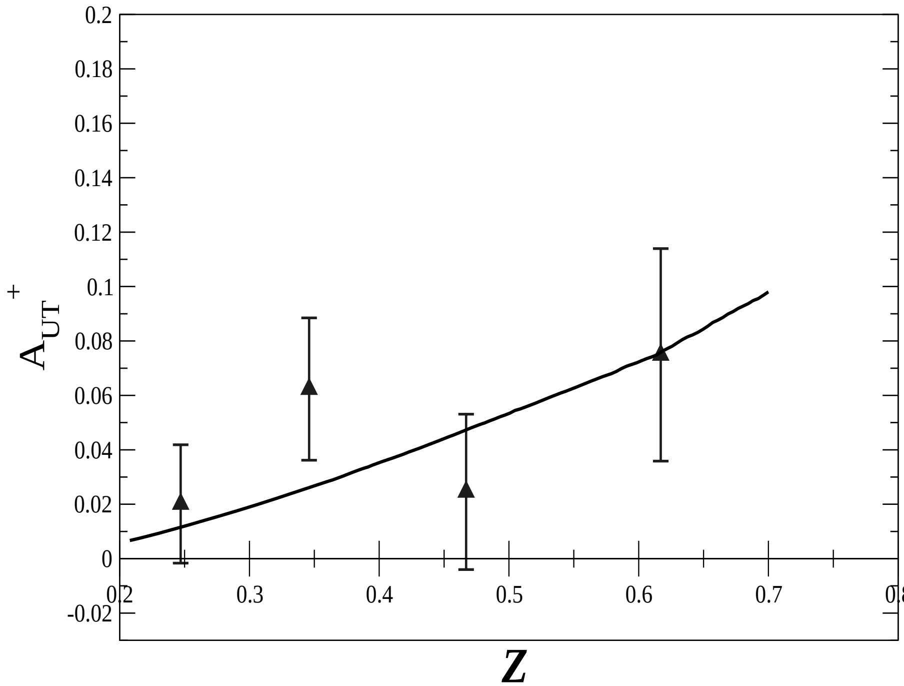
Collins Asymmetry

L.G., 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

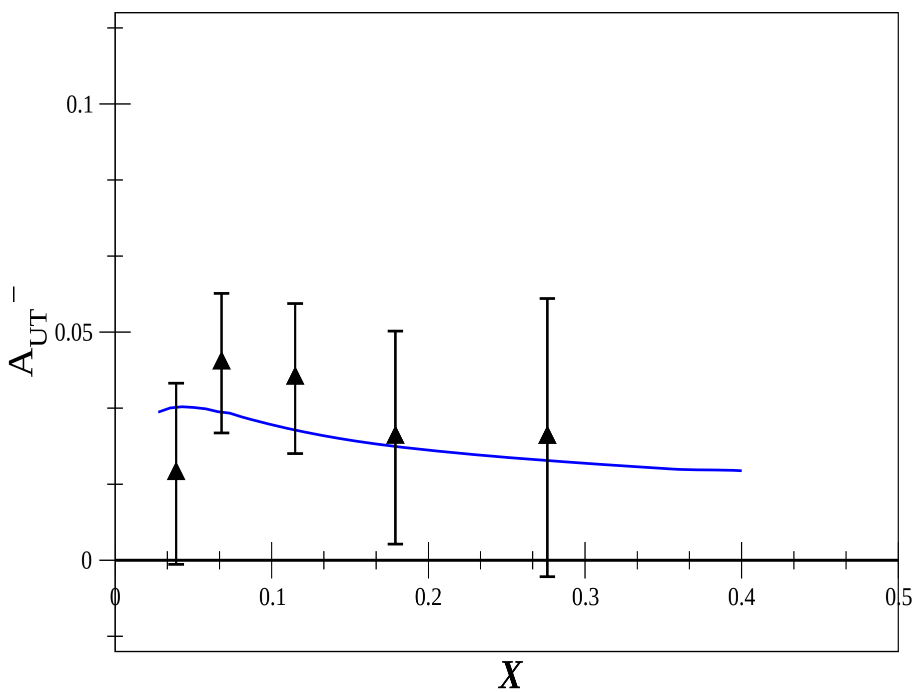


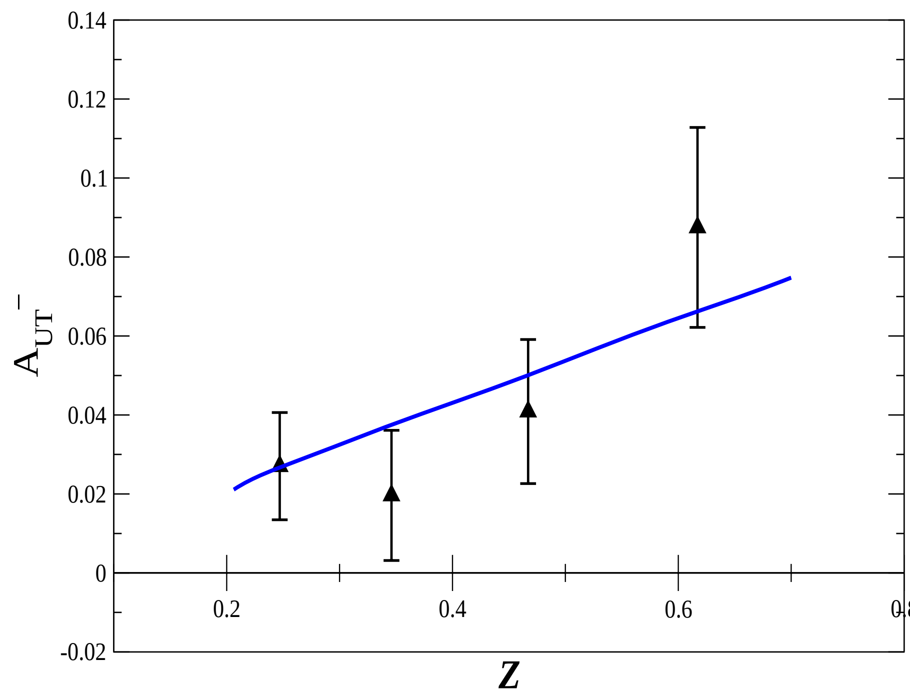


Estimates for Sivers Asymmetry

Data from A. Airapetian et al. PRL94,2005

$$\langle\frac{|P_{h\perp}|}{M}\sin(\phi-\phi_S)\rangle_{UT} \quad = \quad \frac{\int d^2P_{h\perp}\frac{|P_{h\perp}|}{M}\sin(\phi-\phi_S)\,d\sigma}{\int d^2P_{h\perp}\,d\sigma} = \frac{(1+(1-y)^2)\sum_q e_q^2 f_{1T}^{\perp(1)}(x)zD_1^q(z)}{(1+(1-y)^2)\sum_q e_q^2 f_1(x)D_1(z)},$$

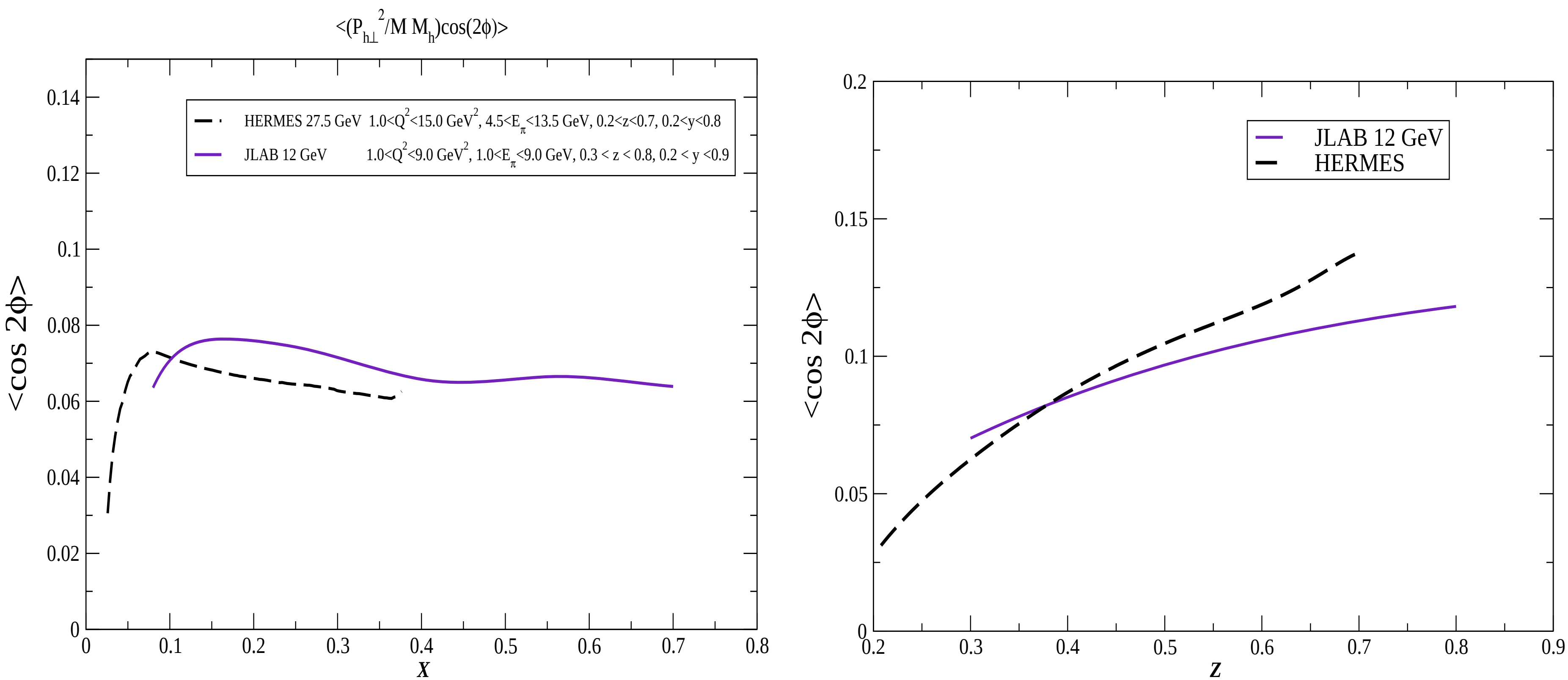




Double T-odd $\cos 2\phi$ asymmetry

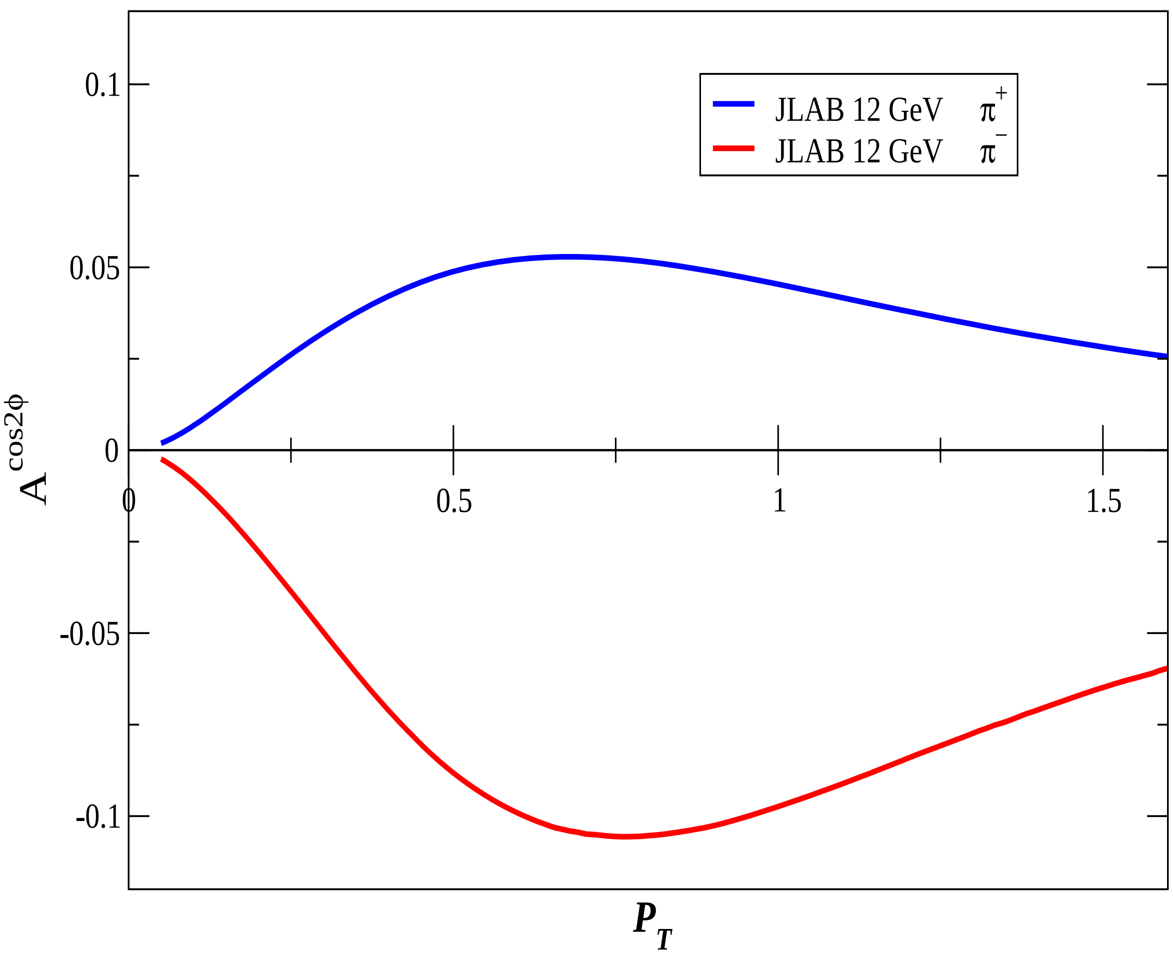
Transversity of quarks inside an unpolarized hadron, and $\cos 2\phi$ asymmetries in unpolarized semi-inclusive DIS

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



CLAS 12 PAC 30

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

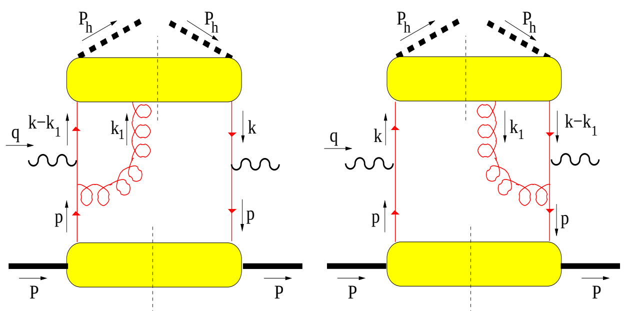


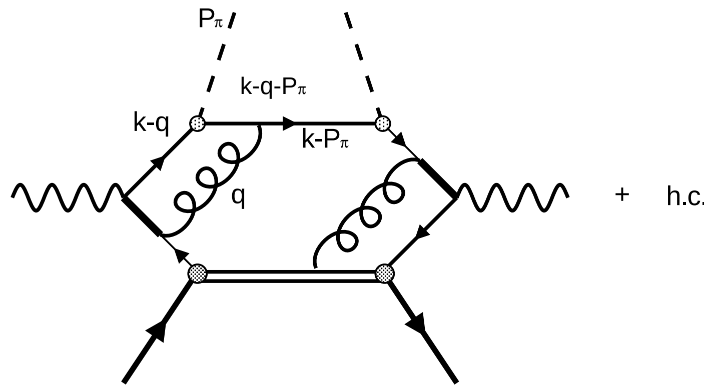
Gauge Link Contribution to Collins Function

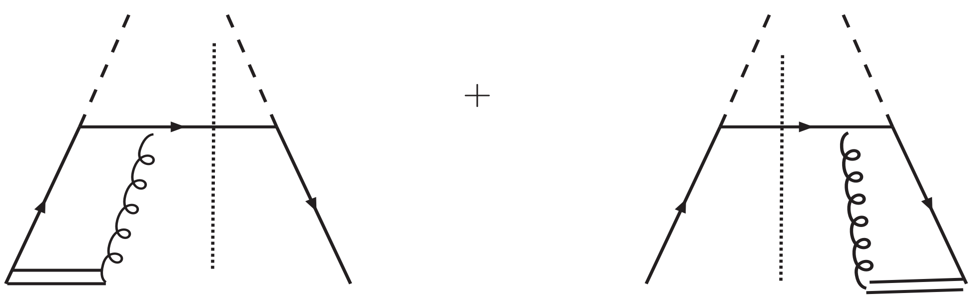
Metz: PBL 2002, L.G., Goldstein, Oganessyan PRD: 2003: Bacchetta, Metz, Jang: PLB: 2003, Amrath, et. al: PRD 2005,

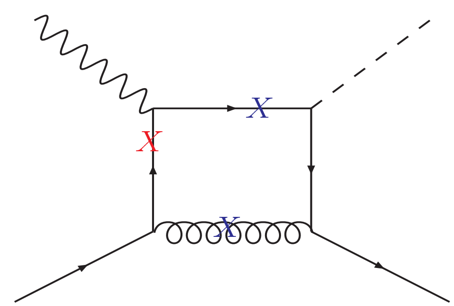
L.G., Goldstein in progress

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









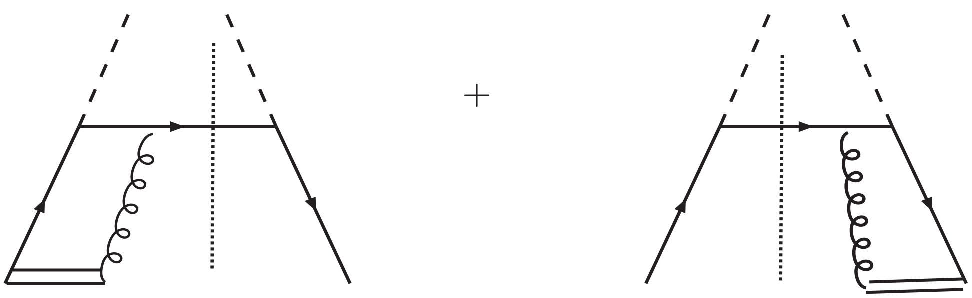
$\frac{i}{\ell^- - i\epsilon}$ $Eikonal\,Feynman\,Rules\,Collins\quad '82'$ $\frac{-i}{\ell^- + i\epsilon}$

On Issues of Process Dependence: Gauge Link Contribution to Fragmentation Function

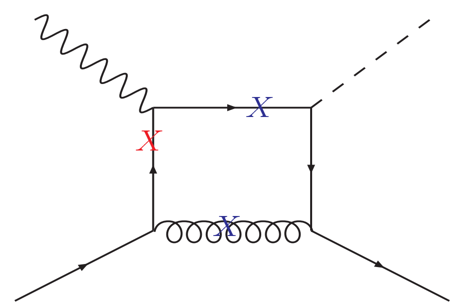
L.G., Goldstein, Oganessyan PRD: 2003: Bacchetta, Metz, Jang: PLB: 2003, Amrath et. al.: PRD 2005,

L.G., G. Goldstein in progress & Como Proceedings 2006

- Boer Piljman and Mulders NPB 2003: Two contributions to the Collins function.
  - ⋆ Gluonic Poles $'' \pm B''$
  - ⋆ FSI "A"
- Does the eikonal pole contribution survive in the "T-Odd" fragmentation function Correlator? Off shell $\gamma + q \to \pi + q'$? Are these the same "processes"?



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



- We explored Pole Structure of correlator
  - ⋆ Use Cauchy's theorem to evaluate the Color Gauge invariant Correlator $\Delta^{[\sigma^{\perp -}\gamma_5]}(z, k_\perp)$

- Analysis of pole structure in ℓ^+indicates a *singular behavior in loop integral-looks like a "lightcone divergence" at first sight*: $\delta(\ell^-)\theta(\ell^-)f(\ell^-)$

⋆ Regulate it keep n off light cone

$$\frac{1}{n \cdot \ell \pm i\epsilon} \quad \cdots$$

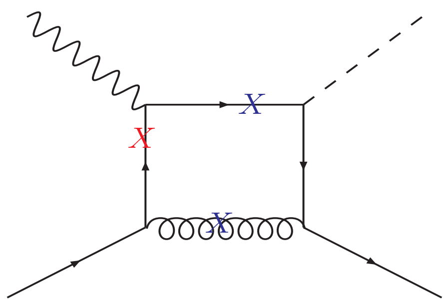
$n = (n^-, n^+, 0)$ (see Collins Soper NPB 1982 Ji, Yuan, Ma PLB: 2004)

⋆ Poles vanish in t-channel

- On Fragmenting quark and gluon $\Rightarrow$ equivalent to cut in S-channel
- On Eikonal and Spectator $\Rightarrow$ equivalent to cut in t-channel

"T-odd" Fragemtation Function universal between e^+e^- and SIDIS

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

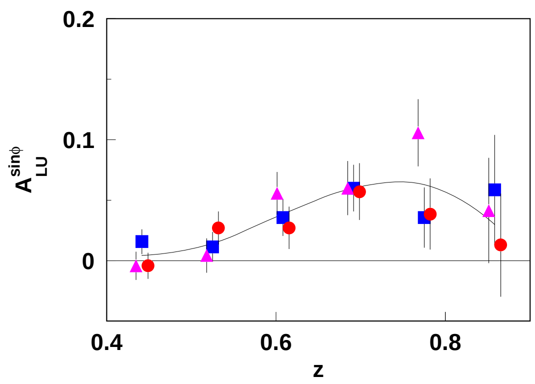
$$\mathcal{I}_1 \quad = \quad \pi(\mu - m(1-z))\frac{E_\pi + P\cos\theta}{P + E_\pi \cos\theta}\left[\ln\frac{(P + E_\pi\cos\theta)^2}{\mu^2} - \cos\theta \ln\frac{4P^2}{\mu^2}\right]$$

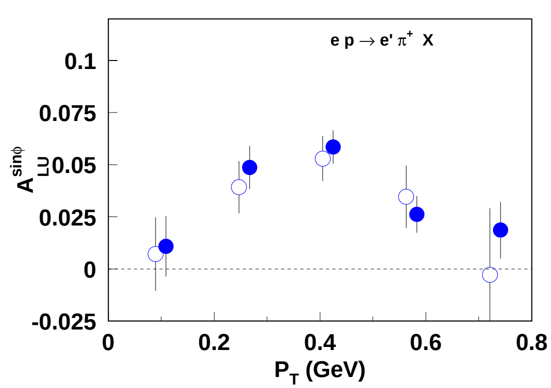
$$\mathcal{I}_2 \quad = \quad \pi\, z\, m\, \frac{P\sin^2\theta}{E_\pi - P\cos\theta}\ln\frac{4P^2}{\mu^2},$$

$P \equiv |\mathbf{P}_h|$ and $P_\perp^2 = k_\perp^2/z^2$. As in the case of the "gluonic pole" contribution, this survives the limit that incoming quark mass $m \to 0$. Both results depend the non-perturbative correlator mass μ.

Beam Spin Asymmetry HERMES and CLAS $\sin\phi \quad \to g^{\perp}$?!

PRD-2004 CLAS Afanasev & Carlson hep-ph/0308163, hep-ph/0603269 Bacchetta et al. PRD 2004, Metz Schlegel EJPA 2004





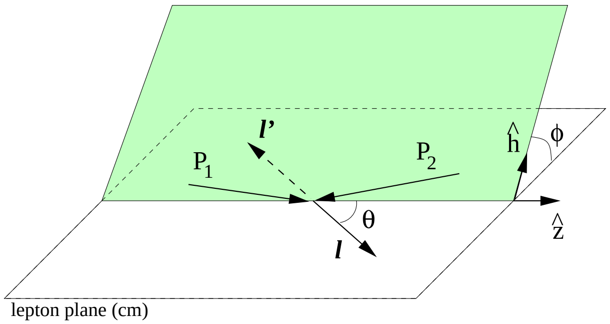
σ_{LU} specify the beam and target polarizations, respectively azimuthal angle ϕ is defined by a triple product:

$$\sin\phi = \frac{[\vec{k}_1 \times \vec{k}_2] \cdot \vec{P}_\perp}{|\vec{k}_1 \times \vec{k}_2||\vec{P}_\perp|} \sim \boldsymbol{S}_{e^-} \cdot \left(\boldsymbol{q}_\gamma \times \boldsymbol{p}\right)$$

Factorization at twist-3 is questionable L.G., Hwang, Metz, Schlegel to appear in PLB 2006

$$\frac{d\sigma_{LU}}{dx_B dy\, dz_h d^2 P_\perp} \propto \lambda_e \sqrt{y^2+\gamma^2}\sqrt{1-y-\frac{1}{4}\gamma^2}\, \sin\phi\ \mathcal{H}'_{LT} \to \frac{g^\perp}{f_1}\ ?$$

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



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

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

Angles refer to the lepton pair orientation in their COM frame relative 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 SoperPRD: 1977 subleading twist

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

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

Higher twist comes in

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

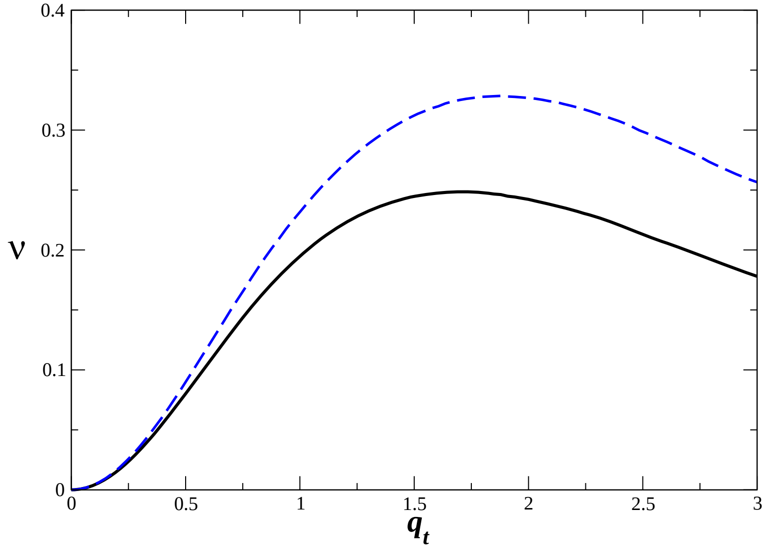
$$\nu_4 = \frac{\frac{1}{Q^2}\sum_a e_a^2 \mathcal{F}\left[w_4\, f_1(x,\boldsymbol{k}_\perp)\bar{f}_1(\bar{x},\boldsymbol{p}_\perp)\right]}{\sum_a e_a^2 \mathcal{F}\left(f_1(x,\boldsymbol{k}_\perp)\bar{f}_1(\bar{x},\boldsymbol{p}_\perp)\right)}$$

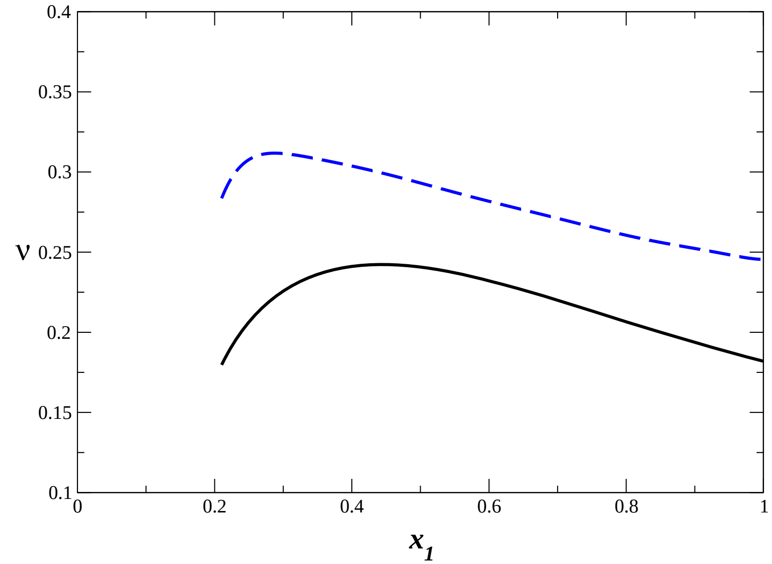
Weight

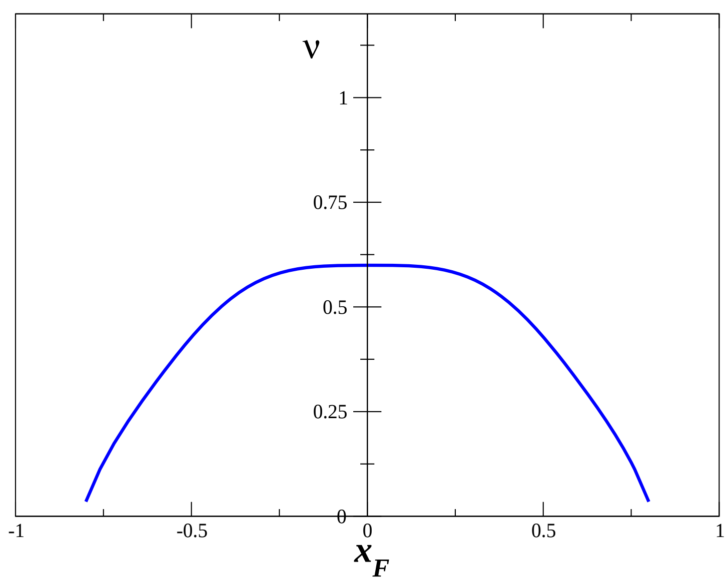
$$w_4 = 2\left(\hat{\boldsymbol{h}} \cdot (\boldsymbol{k}_\perp - \boldsymbol{p}_\perp)\right)^2 - (\boldsymbol{k}_\perp - \boldsymbol{p}_\perp)^2$$

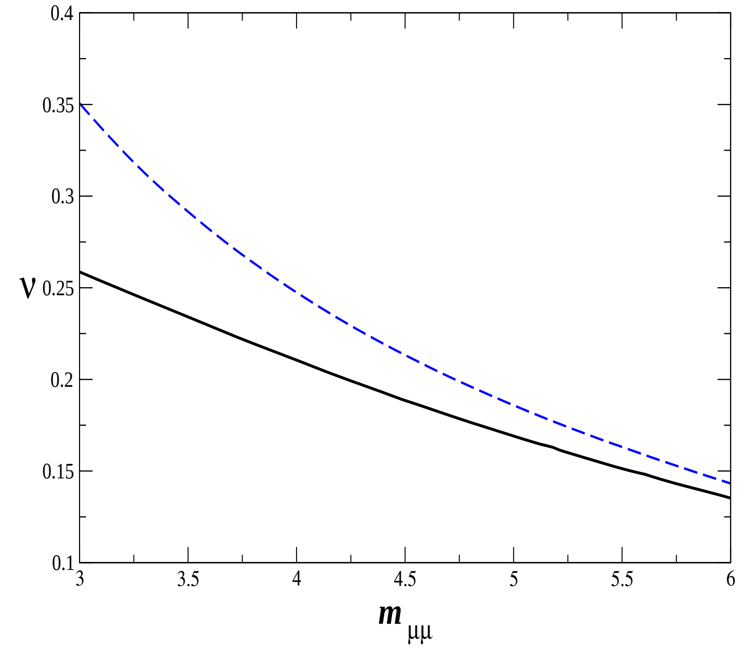
Perform Convolution integral $\mathcal{F} \equiv \int d^2\boldsymbol{p}_\perp d^2\boldsymbol{k}_\perp \delta^2(\boldsymbol{p}_\perp + \boldsymbol{k}_\perp - \boldsymbol{q}_\perp) f^a(x,\boldsymbol{p}_\perp)\bar{f}^a(\bar{x},\boldsymbol{k}_\perp)$

Taking into account further q_T^2/Q^2 corrections $x_1 x_2\, s = Q^2(1 + q_T^2/Q^2)$
i.e. q_T/Q can be order 0.5





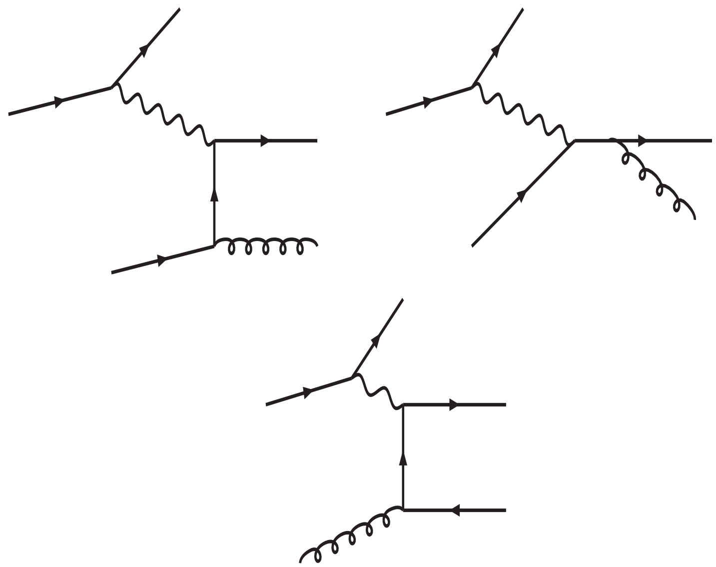




L.G., Goldstein hep-ph/0506127 $s = 50\,GeV^2$, $x = [0.2 - 1.0]$, and $q = [3.0 - 6.0]\ GeV$, $\boldsymbol{q_T} = 0 - 3.0\,GeV$

$\cos 2\phi$ and EIC

- Georgi and Mendez 1975, gluon PQCD "....
- gluon bremstrulang competes with convolution of $h_1^\perp \otimes H_1^\perp$
- Qui Sterman Ji Yuan Vogelsang approach 2006



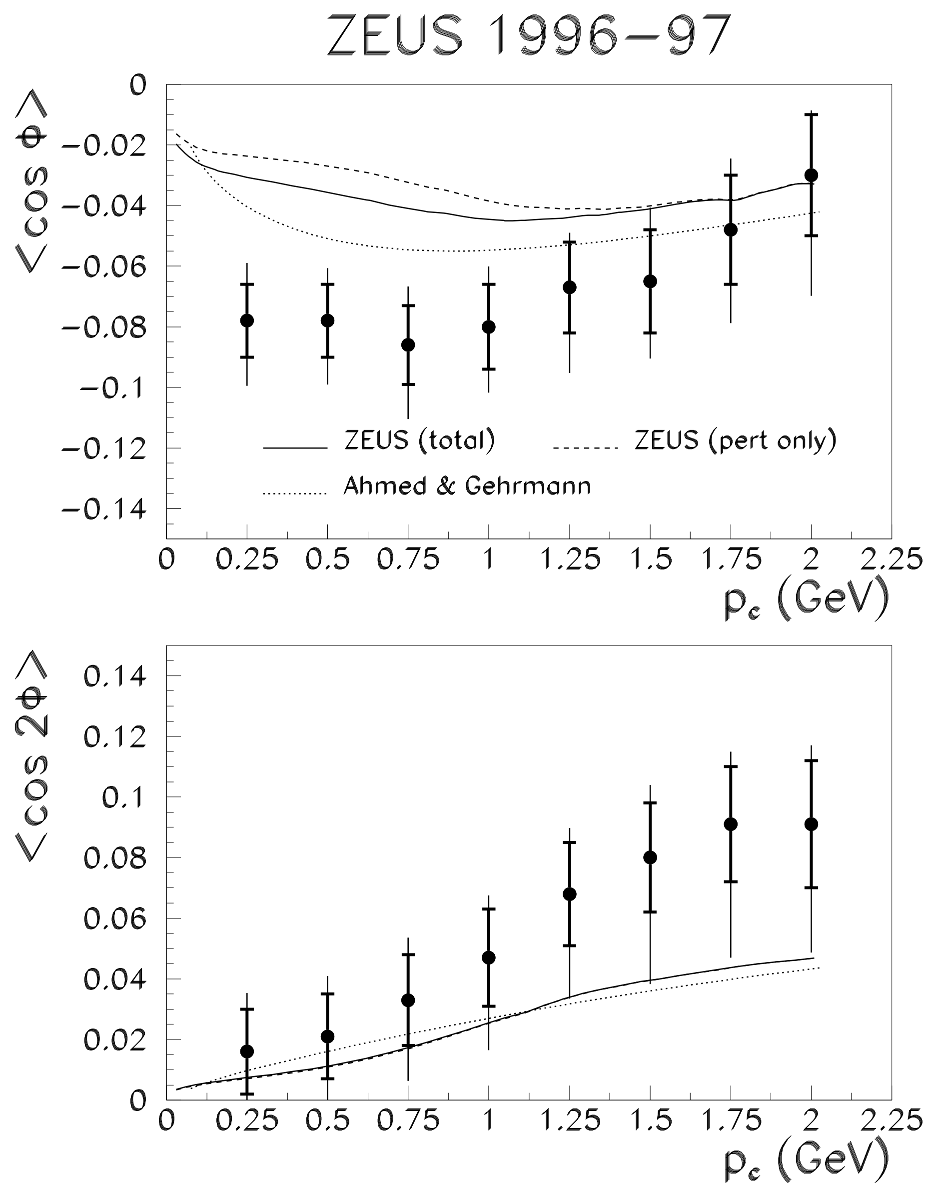


Figure 4: The values of $\langle\cos\phi\rangle$ and $\langle\cos 2\phi\rangle$ are shown as a function of p_c in the kinematic region $0.01 < x < 0.1$ and $0.2 < y < 0.8$ for charged hadrons with $0.2 < z_h < 1.0$. The inner error bars represent the statistical errors, the outer are statistical and systematic errors added in quadrature. The lines are the LO predictions from ZEUS with perturbative and non-perturbative contributions (full line), ZEUS with the perturbative contribution only (dashed line) and Ahmed & Gehrmann (dotted line – see text for discussion). For the case of $\langle\cos 2\phi\rangle$, the ZEUS total and perturbative predictions are almost identical.

SUMMARY

- Going beyond the collinear approximation in PQCD recent progress has been achieved 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 should consider the angular correlations in SDIS at 12 GeV for $\cos 2\phi$ from the standpoint of "rescattering" mechanism which generate T-odd, intrinsic transverse momentum, $k_\perp$, dependent *distribution and fragmentation* functions at leading twist
- Addressing issues of universality of Collins Function in spectator framework

⋆ Azimuthal asymmetries in Drell Yan and SSA measured at HERMES and COMPASS, JLAB, Belle, GSI-PAX, JPARC *may* reveal the extent to which these leading twist T-odd effects are generating the data