

“Transverse Quark-Spin Effects in SIDIS”

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Penn State Berks

Deep Inelastic Scattering 2007



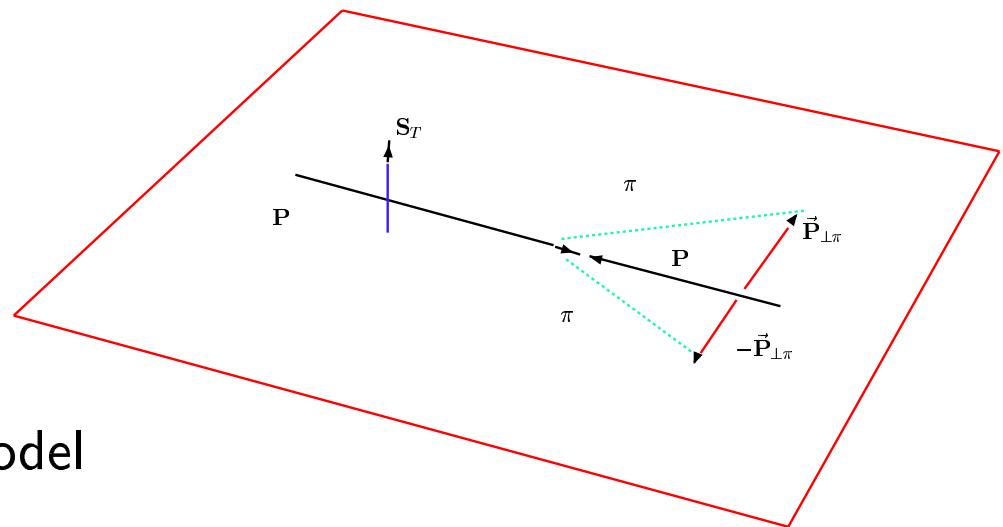
- Remarks Transverse Spin effects in TSSAs and AAs in QCD
- * Reaction Mechanisms: Beyond Co-linearity ISI/FSI Twist Two vs. Colinear-limit ETQS-Twist Three
- * Unintegrated PDF “ T -odd” TMDs Distribution and Fragmentation Functions
Correlations btwn intrinsic k_{\perp} , transverse spin S_T
- * T -odd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

* G. R. Goldstein (Tufts), Marc Schlegel (JLAB), A. Bacchetta (DESY), A. Mukherjee (ITT, Bombay)



Transverse SPIN Observables SSA (TSSA)

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



- * Co-linear factorized QCD-parton model

$$\Delta\sigma \sim f_a \otimes f_b \otimes \hat{\sigma} \otimes D^{q \rightarrow \pi}$$

Requires helicity flip in hard part $\hat{\sigma}$

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

- * Requires relative phase btwn helicity amps

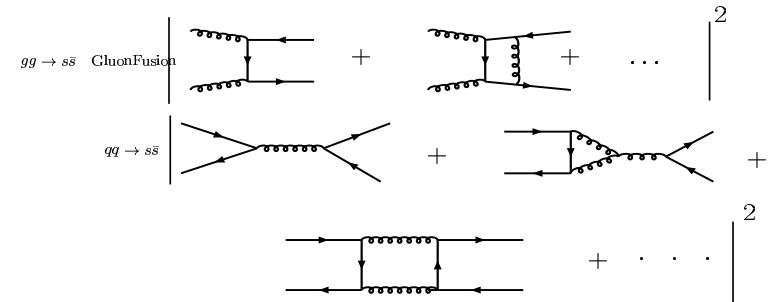
- QCD interactions conserve helicity $m_q \rightarrow 0$ & Born amplitudes real!

- * Generally interference btwn loops-tree level $A_N \sim \frac{m_q \alpha_s}{P_T}$ small Kane, Repko, PRL:1978

Early test- Λ Production ($pp \rightarrow \Lambda^\uparrow X$) Dharmarntna & Goldstein PRD 1990

- Need strange quark to polarize a Λ

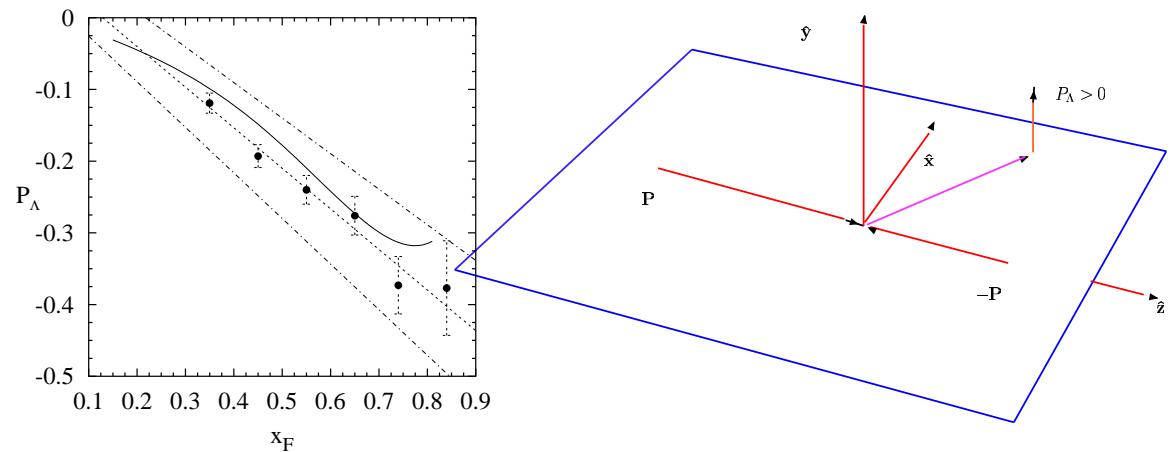
$$P_\Lambda = \frac{d\sigma^{pp \rightarrow \Lambda^\uparrow X} - d\sigma^{pp \rightarrow \Lambda^\downarrow X}}{d\sigma^{pp \rightarrow \Lambda^\uparrow X} + d\sigma^{pp \rightarrow \Lambda^\downarrow X}}$$



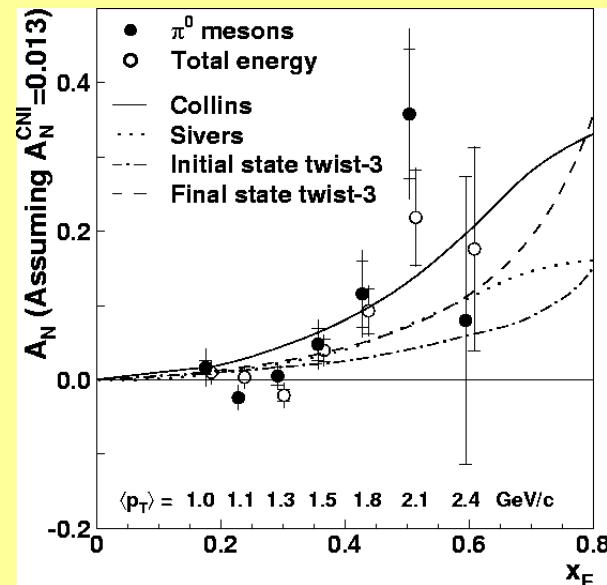
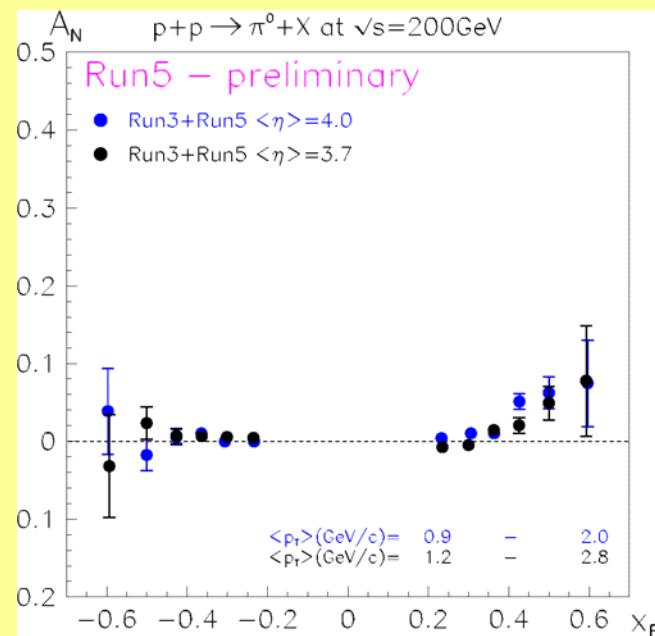
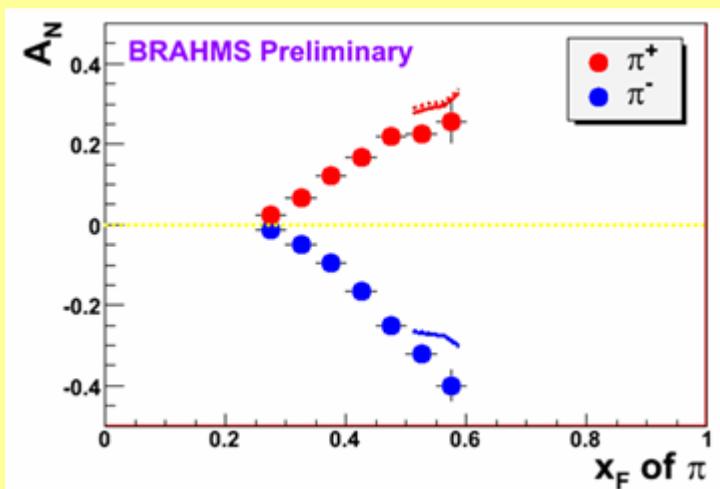
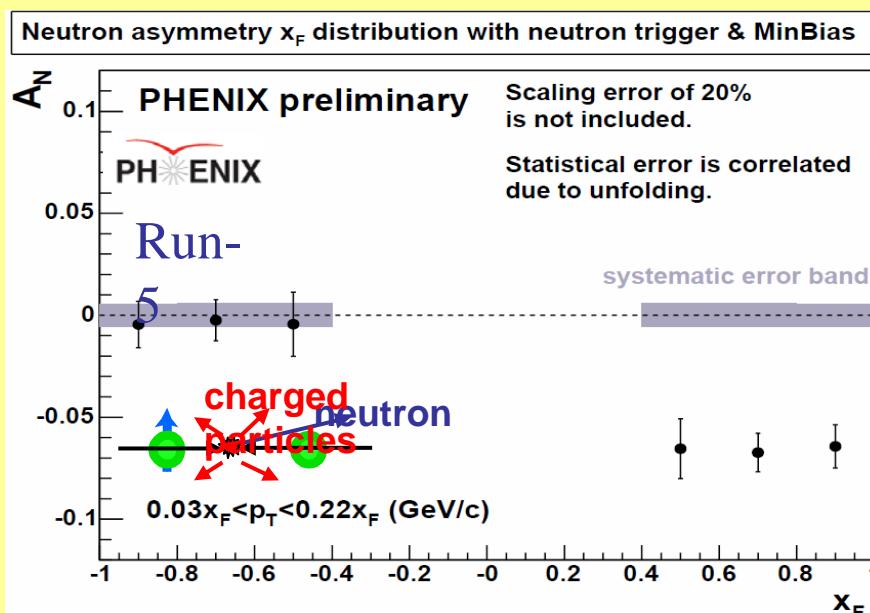
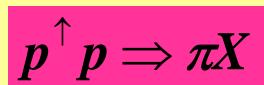
Phases in *hard part* $\hat{\sigma}$
interference of loops and tree level

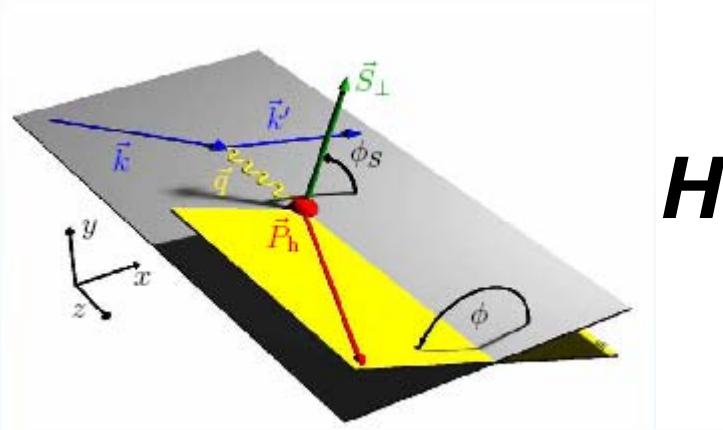
- Polarization $P_\Lambda \sim \frac{m_s \alpha_s}{P_T}$ -twist 3 & small $\approx 5\%$ as predicted
- Experiment *glaringly at odd with this result*

P_Λ in $p-p$ scattering-Fermi Lab
Heller,...,Bunce PRL:1983

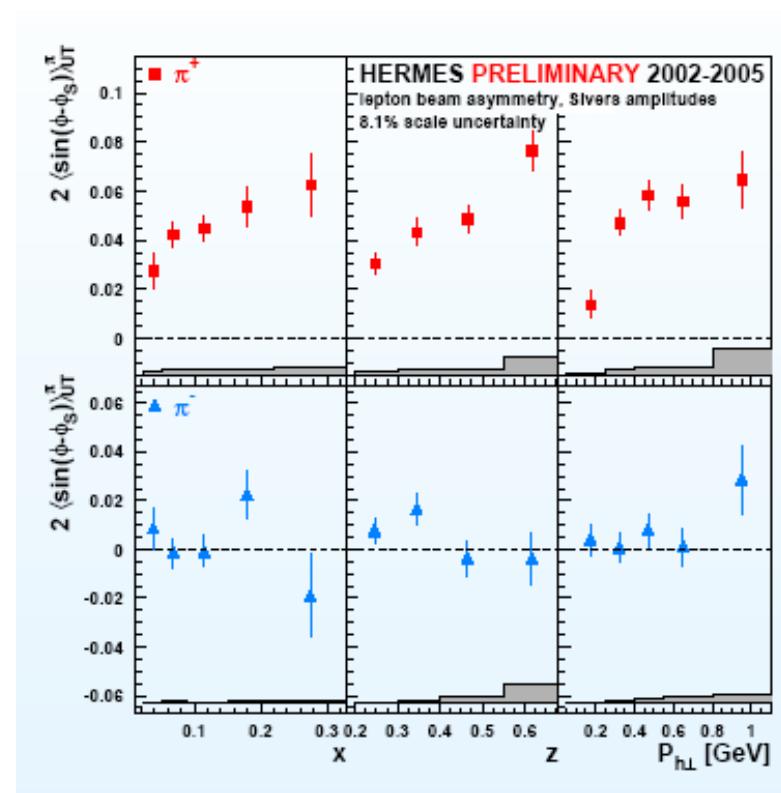
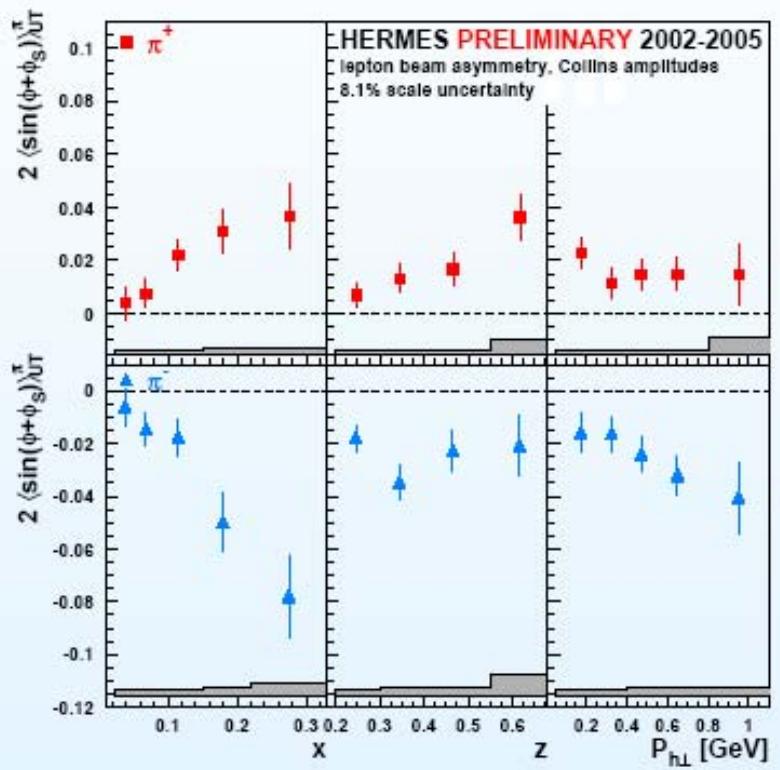


E704 and BNL

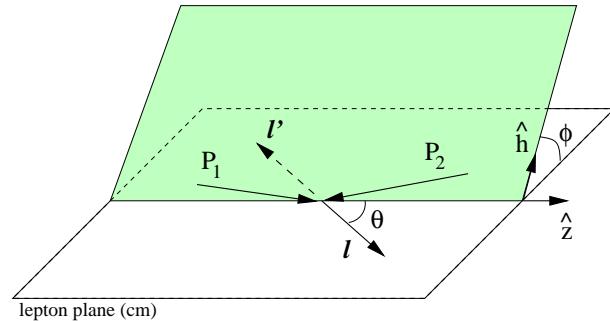




HERMES

$$ep^{\uparrow} \Rightarrow \pi X$$


Azimuthal Asymmetry–Unpolarized DRELL YAN



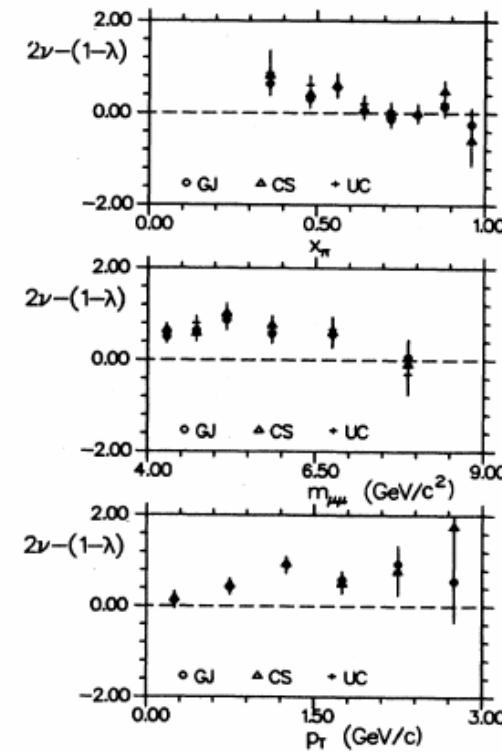
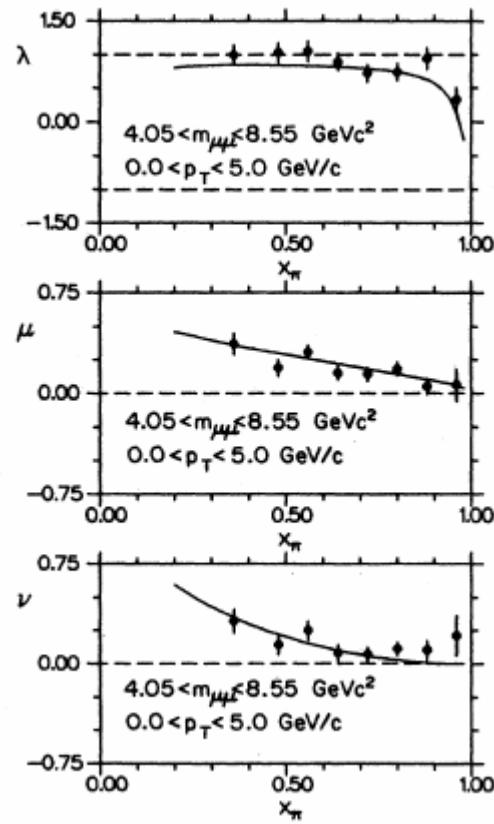
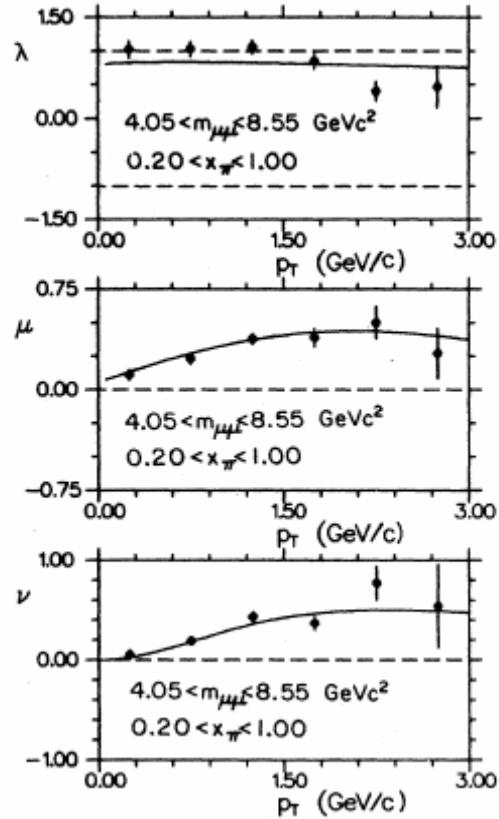
E615, Conway et al. 1986, $\pi^- + p \rightarrow \mu^+ + \mu^- + X$ NA10, ZPC, 1986

QCD-Parton Model doesn't account for large “AA”

λ, μ, ν depend on $s, x, m_{\mu\mu}^2, p_T$

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

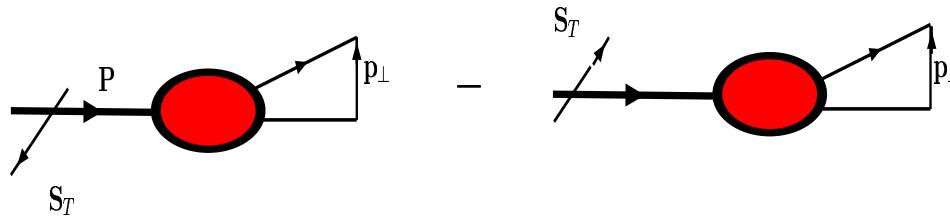
- NNLO QCD predict Lam-Tung relation $1 - \lambda - 2\nu = 0$
(Mirkes Ohnemus, PRD 1995)
- *Unexpected large* $\cos 2\phi - \nu \sim 10 - 30\%$ AA



Lam-Tung Relationship Violated

$p_T \sim k_\perp$ TSSAs thru “*T*-Odd” TMD

- Sivers PRD: 1990, TSSA associated with “*T*-odd” correlation of *transverse* spin and momenta Correlation accounts for left-right TSSA

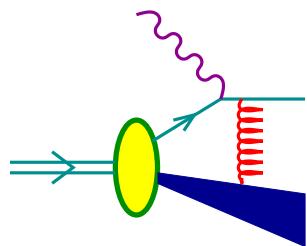


$$\Delta\sigma \sim D \otimes f \otimes \Delta f^\perp \otimes \hat{\sigma}_{Born} \quad iS_T \cdot (P \times k_\perp) \rightarrow f_{1T}^\perp(x, k_\perp)$$

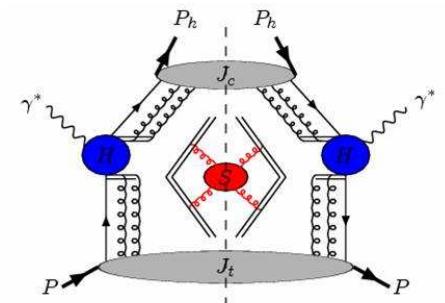
- SIDIS w/ transverse polarized nucleon target $e p^\perp \rightarrow \pi X$

BHS, PLB: 2002 FSI produce phase in TSSAs-*Leading Twist*

Ji, Yuan PLB: 2002 -Sivers fnct. FSI emerge from Color Gauge-links



$$\Delta\sigma \sim D \otimes \Delta f^\perp \otimes \hat{\sigma}_{Born}$$



Ji, Ma, Yuan: PLB, PRD 2004, 2005 extend factorization of CS-NPB: 81

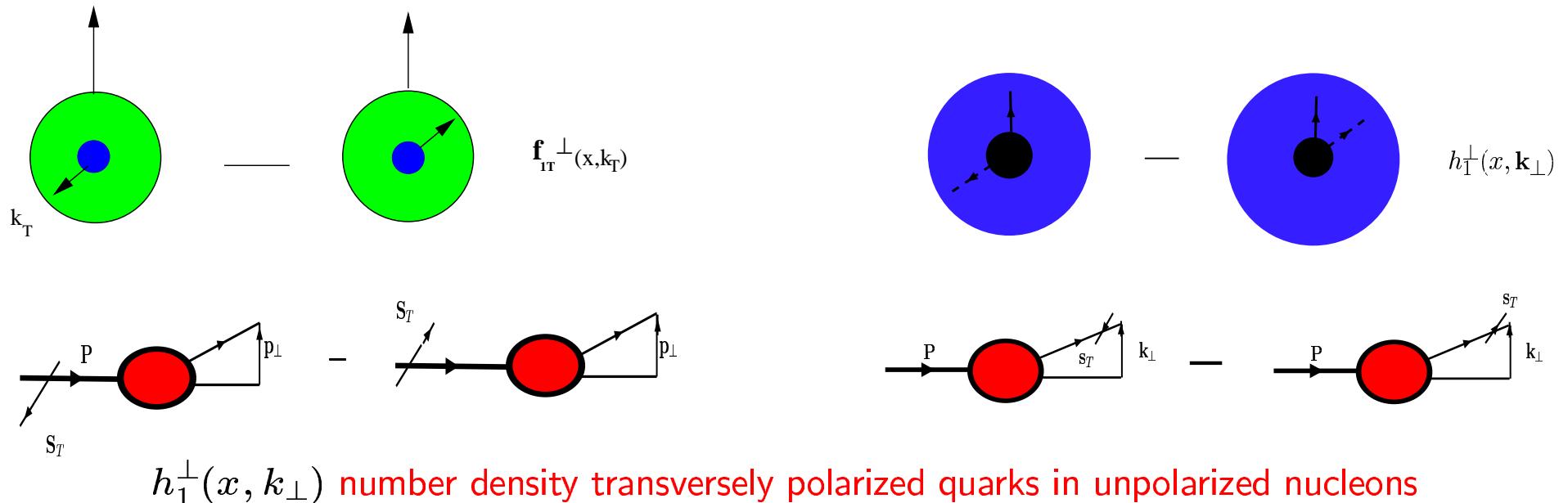
Collins, Metz: PRL 2005 *Universality & Factorization “Maximally” Correlated*

Transversity w/o Target Polarization

Transversely polarized quark in unpolarized Target [Boer,Mulders PRD: 1998](#)

Correlation of transversely polarized *quark spin*
with intrinsic \mathbf{k}_\perp

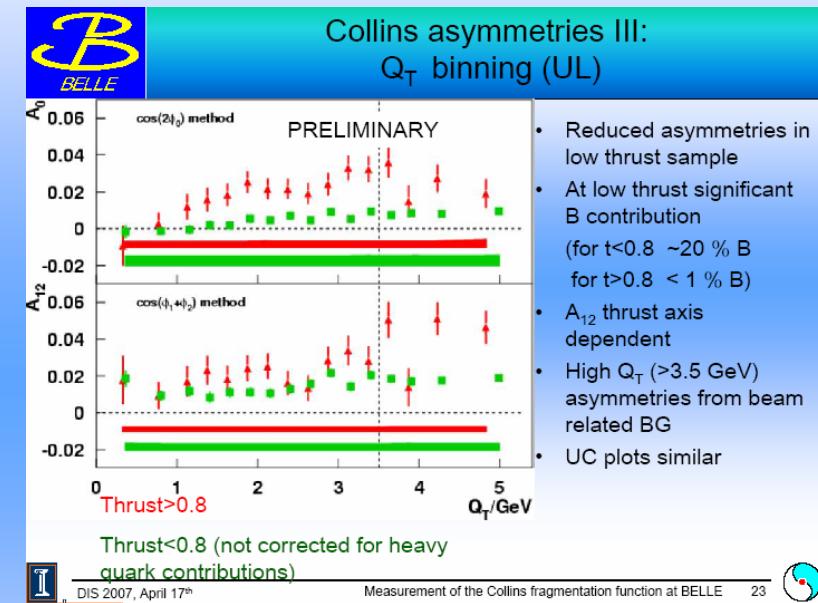
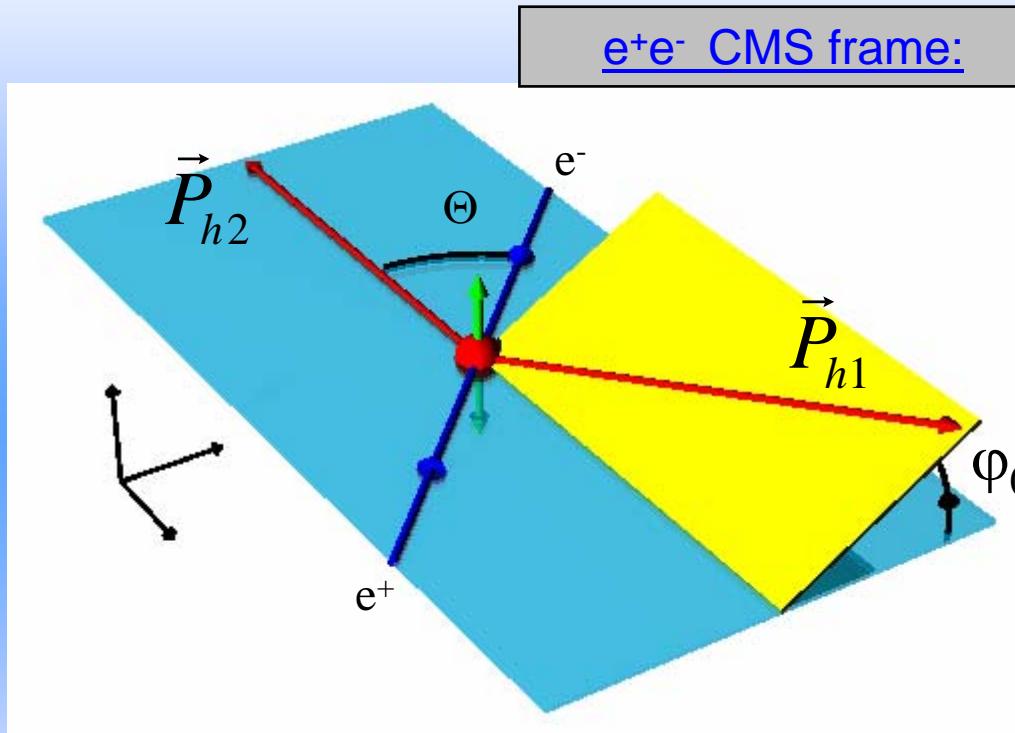
$$is_T \cdot (\mathbf{k}_\perp \times \mathbf{P}) \rightarrow h_1^\perp(x, \mathbf{k}_\perp)$$



* Boer, Mulders PRD: 1998 $\cos 2\phi$ -AA in unpolarized lepto-production $e P \rightarrow e' \pi X$

* Boer PRD: 1999 $\cos 2\phi$ -AA in Drell Yan $\pi^- + p \rightarrow \mu^+ + \mu^- + X$ or $\bar{p} + p \rightarrow \mu^- \mu^+ + X$
(cleaner-no Fragmentation)

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



$$\frac{d\sigma(e^+e^- \rightarrow h_1 h_2 X)}{d\Omega dz_1 dz_2 d^2 q_T} = \dots B(y) \cos(2\phi_0) I \left[(2\hat{h} \cdot k_T \hat{h} \cdot p_T - k_T \cdot p_T) \frac{\mathbf{H}_1^\perp \bar{\mathbf{H}}_1^\perp}{M_1 M_2} \right]$$

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



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

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

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

SIDIS cross section

$$d\sigma_{\{\lambda, \Lambda\}}^{\ell N \rightarrow \ell \pi X} \propto f_1 \otimes d\hat{\sigma}^{\ell q \rightarrow \ell q} \otimes D_1 + \frac{k_\perp}{Q} f_1 \otimes d\hat{\sigma}^{\ell q \rightarrow \ell q} \otimes D_1 \cdot \cos \phi$$

$$+ \left[\frac{k_\perp^2}{Q^2} f_1 \otimes d\hat{\sigma}^{\ell q \rightarrow \ell q} \otimes D_1 + h_1^\perp \otimes d\hat{\sigma}^{\ell q \rightarrow \ell q} \otimes H_1^\perp \right] \cdot \cos 2\phi$$

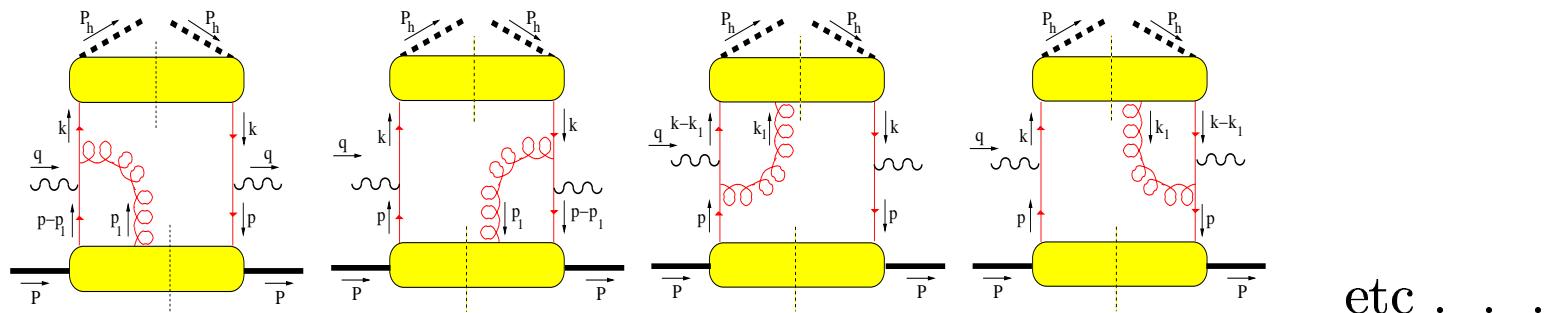
$$+ |S_T| \cdot h_1 \otimes d\hat{\sigma}^{\ell q \rightarrow \ell q} \otimes H_1^\perp \cdot \sin(\phi + \phi_S) \quad \text{Collins}$$

$$+ |S_T| \cdot f_{1T}^\perp \otimes d\hat{\sigma}^{\ell q \rightarrow \ell q} \otimes D_1 \cdot \sin(\phi - \phi_S) \quad \text{Sivers}$$

$$+ \dots$$

T-Odd Effects Naturally Incorp. in Color Gauge Invariant Factorized QCD thru Wilson Line

- Leading twist Gauge Invariant Distribution and Fragmentation Functions
Boer, Mulders: NPB 2000, Ji et al PLB: 2002, NPB 2003, Boer et al NPB 2003



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

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

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

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

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

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

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

- The INPUT

- Boer Mulders
- Collins Function

- Theoretical Issues

- Sign of Boer Mulders
- Universality of Collins Function

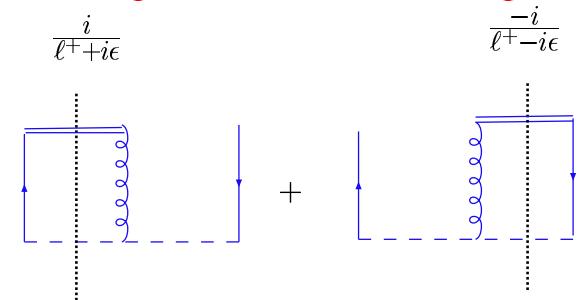
Addressed thru Estimates of T-odd Contribution in SIDIS:

Impacts predictions at (HERMES, JLAB 6 & 12 GeV program)

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

- * In spectator framework point-like nucleon-quark-diquark vertex **logarithmically divergent asymmetries**, Goldstein, L.G., ICHEP 2002; hep-ph/0209085)

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



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

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

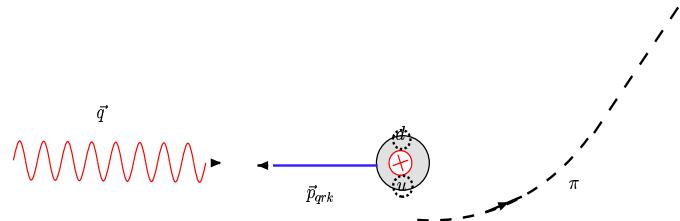
with

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

Quark Transversity & Boer Mulders Function

GPDs-Impact Parameter PDFs

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



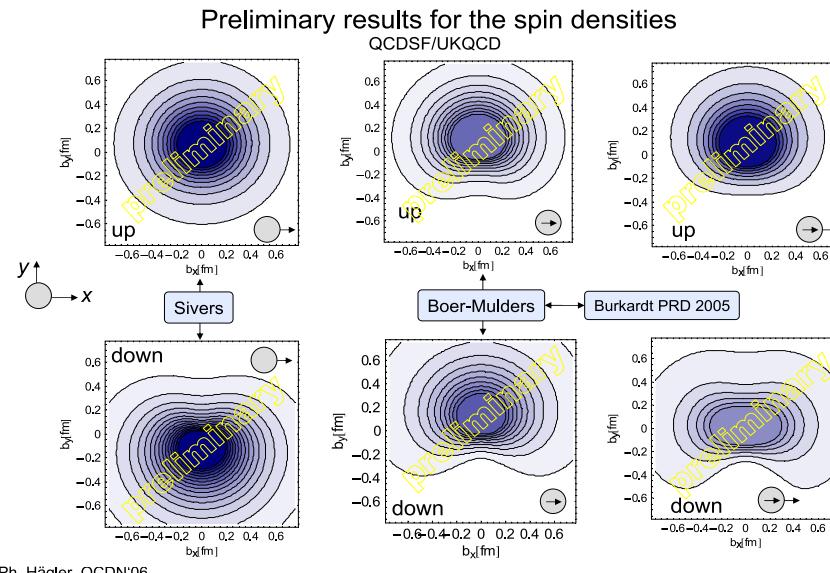
- $\delta q^X(x, \mathbf{b}_\perp) \leftrightarrow h_1^{\perp q}$ WHERE $\delta q^X(x, \mathbf{b}_\perp) = -\frac{1}{2M} \frac{\partial}{\partial b_y} (2\tilde{\mathcal{H}}_T(x, \mathbf{b}_\perp) + \mathcal{E}_T(x, \mathbf{b}_\perp))$
 - ★ $d_y^q = \int dx \int d^2 \mathbf{b}_\perp \delta q^X(x, \mathbf{b}_\perp) b_y = \kappa_T^q / 2M$
- *Transverse distortion* in impact parameter space of transversely polarized quarks in an unpolarized nucleon [Burkardt PRD 2005](#), [Diehl, Hägler EPJC 2005](#)
 - ★ Implies up and down quark Boer Mulders function-same sign!

- Supports

- ★ $\text{Lg } N_C$ arguments [Pobylitsa hep-ph/0301236](#)
- ★ Bag Model calculation [Yuan PLB 2003](#)
- ★ Implications $\cos 2\phi$ phenomenology in SIDIS & Drell Yan
- Lattice QCDSF/UKQCD, Hägler et al... calculations of matrix elements on the lattice

$$\kappa_T = \int dx \bar{E}_T(x, \xi, t=0) \equiv \bar{B}_{T10}(t=0)$$

$$\kappa_T^{(u)} = \kappa_T^{(d)}$$



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see talks of Hägler's and Metz



DIS 2007, MUNICH- April 17th 2007

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

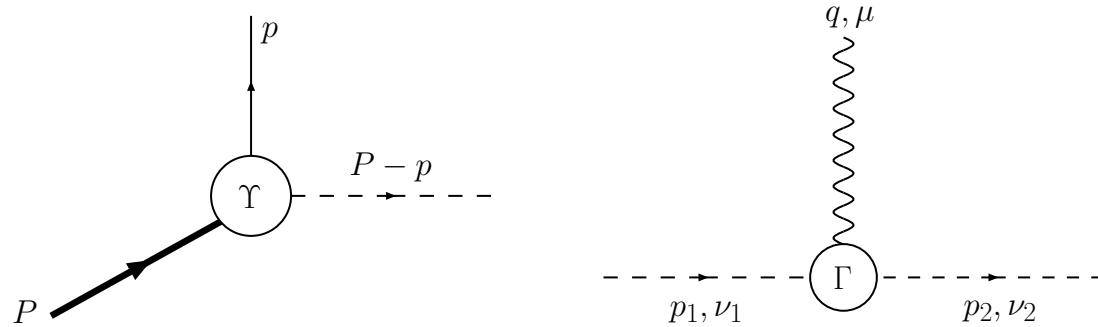
Correlator

$$\Phi_{ij}(p; P, S) = \sum_{\lambda} \frac{1}{(2\pi)^3} \delta((P - p)^2 - m_s^2) \Theta(P^0 - p^0)$$

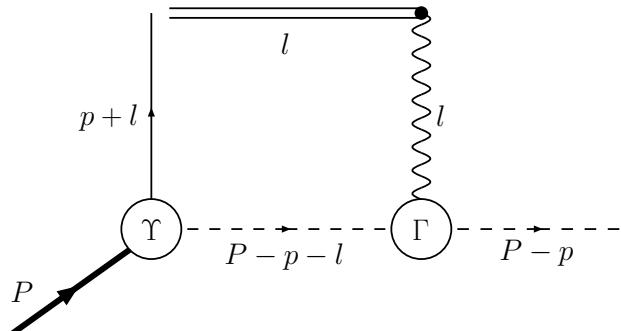
$$\langle P, S | \bar{\psi}_j(0) \mathcal{W}[0 | \infty, 0, \vec{0}_T] | dq; P - p, \lambda \rangle \langle dq; P - p, \lambda | \mathcal{W}[\infty, 0, \vec{0}_T | 0] \psi_i(0) | P, S \rangle.$$

$$\Upsilon_{ax}^\mu(N) u(P) = \frac{g_{ax}(\frac{p^2}{M^2})}{\sqrt{3}} \gamma_5 \left[\gamma^\mu - Rg \frac{P^\mu}{M} \right] u(P)$$

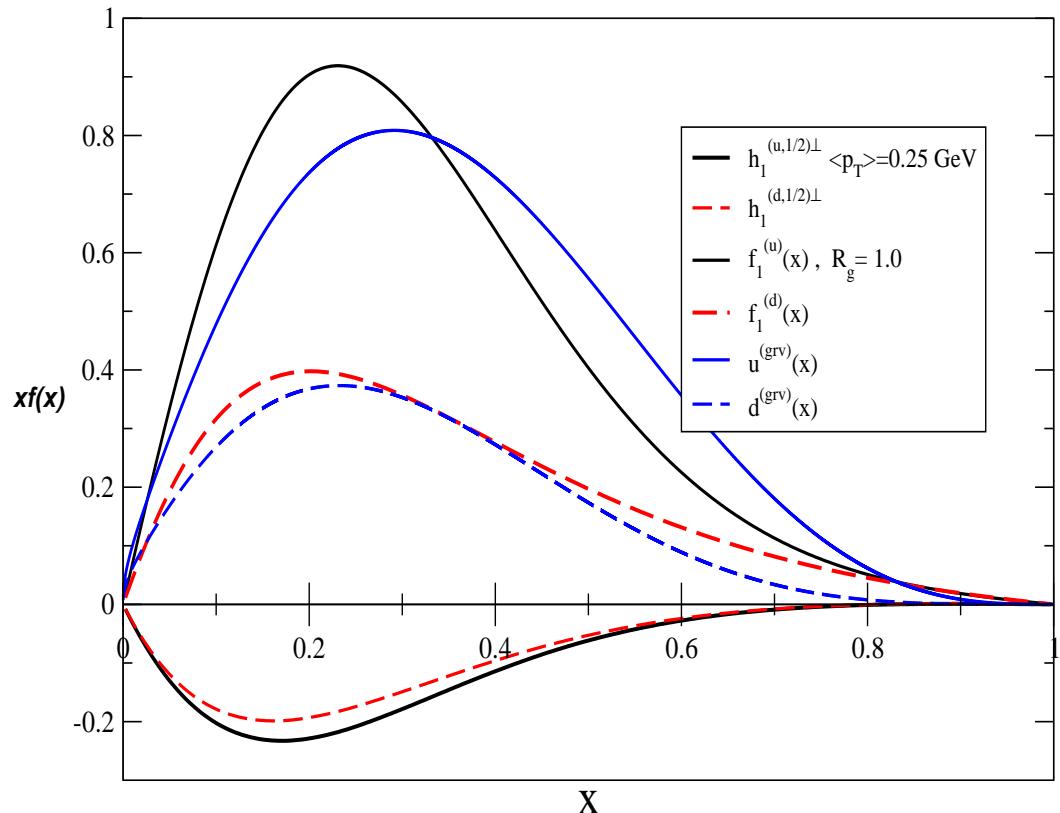
$$\Gamma_{ax}^{\mu\nu 1 \nu 2} = -ie_{dq} \left[g^{\nu 1 \nu 2} (p_1 + p_2)^\mu - g^{\mu\nu 2} (p_2 + q)^\nu 1 - g^{\mu\nu 1} (p_1 - q)^\nu 2 \right]$$



Entering



Boer Mulders Function for up and down flavors
 $m_q=0.35, M_N=0.94, m_s=1.0, M_d=1.2, \Lambda=1.0$

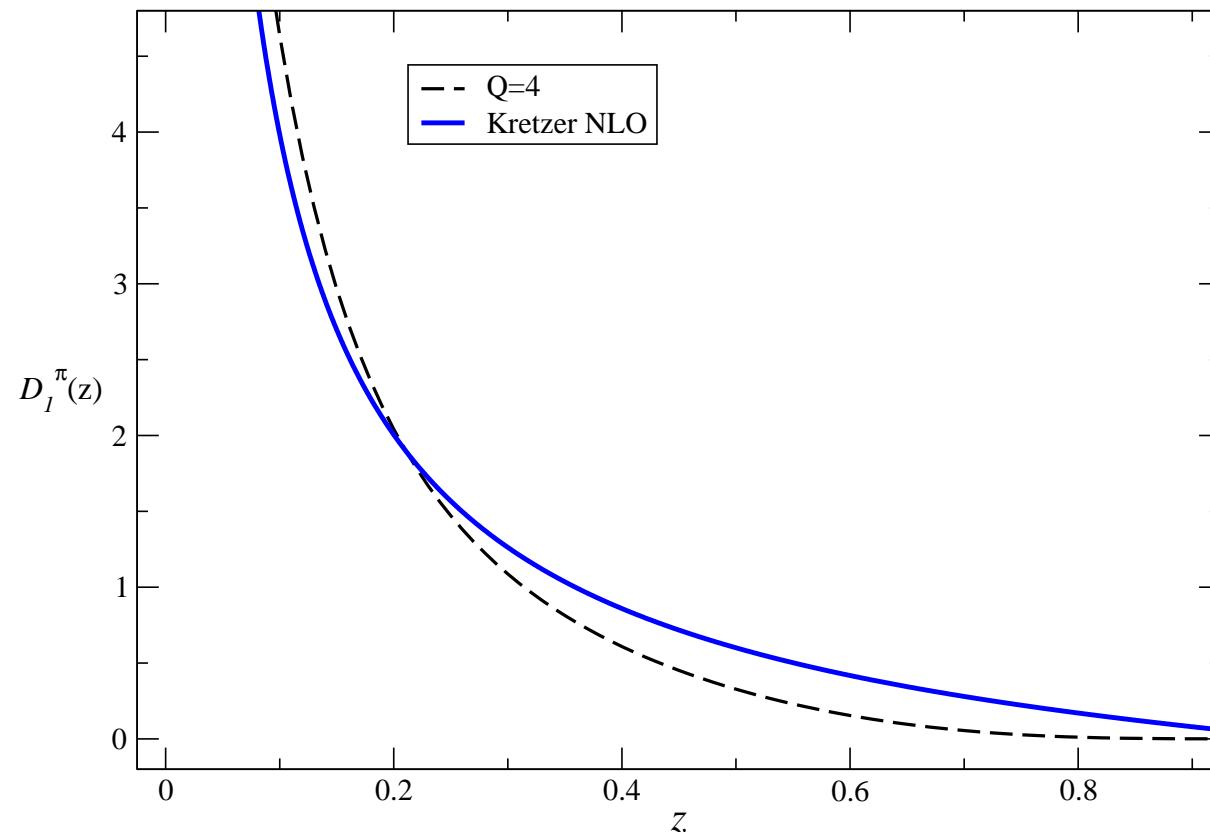


- ★ Valence Normalization, $\int_0^1 u(x) = 2, \int_0^1 d(x) = 1$
- Black curve- $xu(x)$
- Dashed curve - $xu(x)$ GRV
- Red/Blue curve $xh_1^{\perp(1/2)(u,d)}$

Pion Fragmentation Function

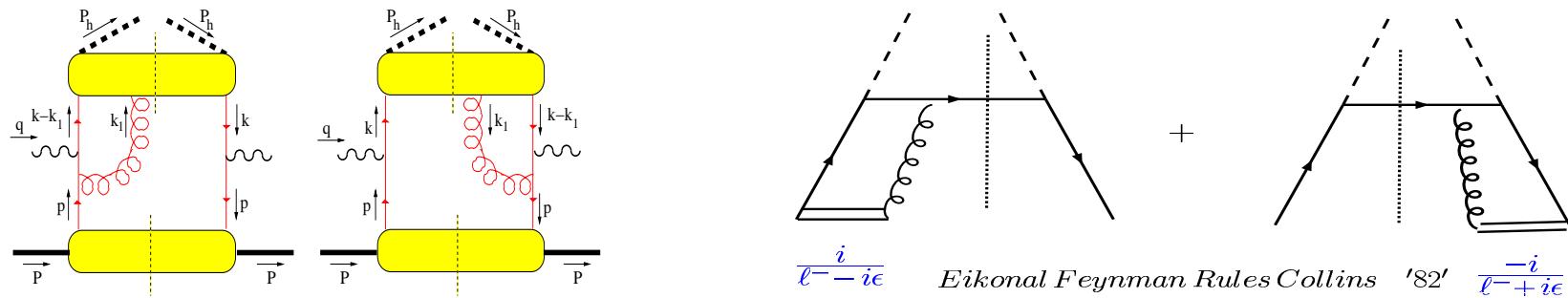
Bacchetta, L.G., Goldstein, Mukherjee in prep

Normalized to Kretzer, PRD: 2000



Gauge Link Contribution to T -Odd Collins Function

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



Motivation: color gauge .inv frag. correlator

“pole contribution” Gribov-Lipatov Reciprocity 1974, Mulders et al. 1990s

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 & Como Proceedings 2006

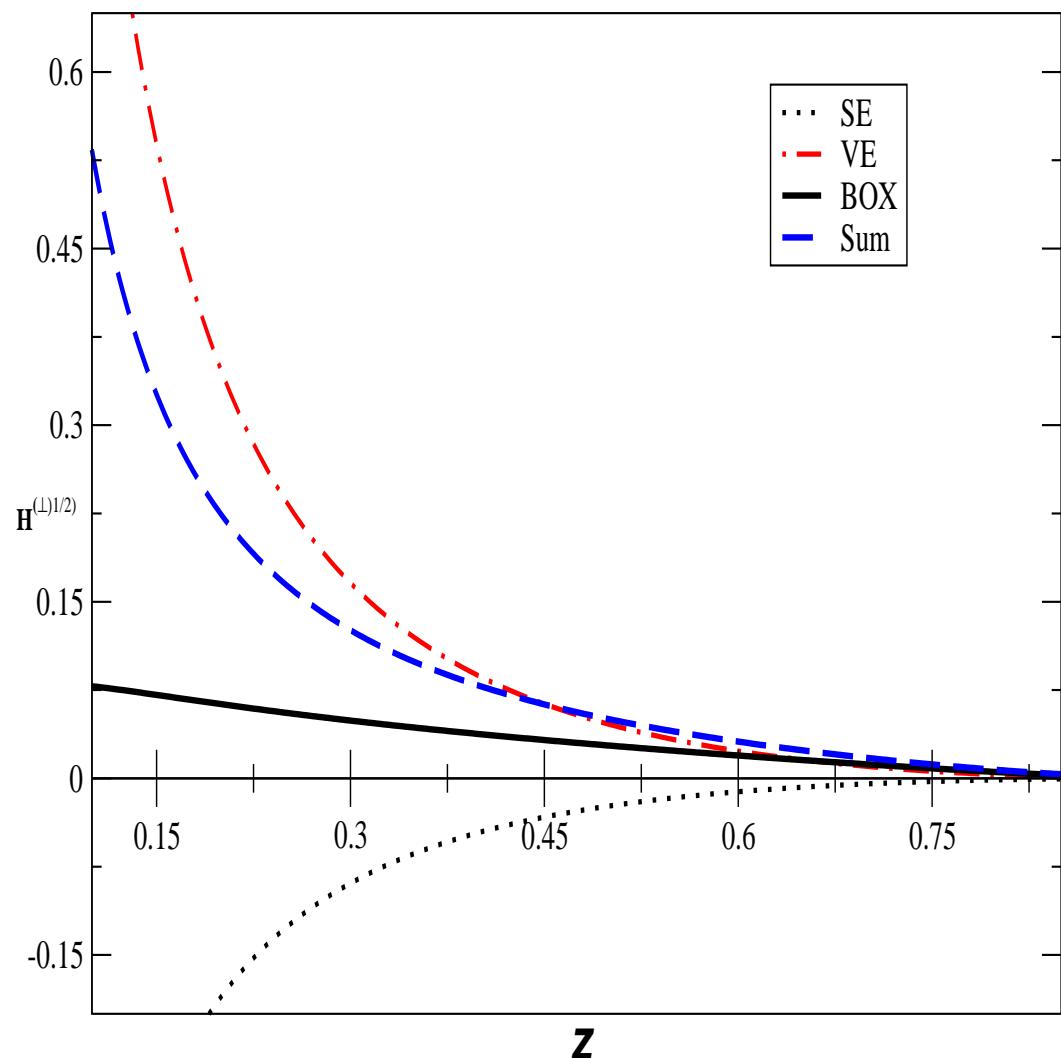
- * Collins Metz PRL proves Universality basis for cut method of Bacchetta et al.
- * Another argument in spectator model use Cauchy's theorem to evaluate the Color Gauge invariant Correlator $\Delta^{[\sigma^\perp - \gamma_5]}(z, k_\perp)$
- Analysis of pole structure in ℓ^+ indicates a *singular behavior in loop integral-looks like a "lightcone divergence" at first sight*: $\delta(\ell^-)\theta(\ell^-)f(\ell^-)$
- $f(\ell^-)$ polynomial in ℓ^- -vanishes...
- * Regulate it keep n off light cone, outside physical regime

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

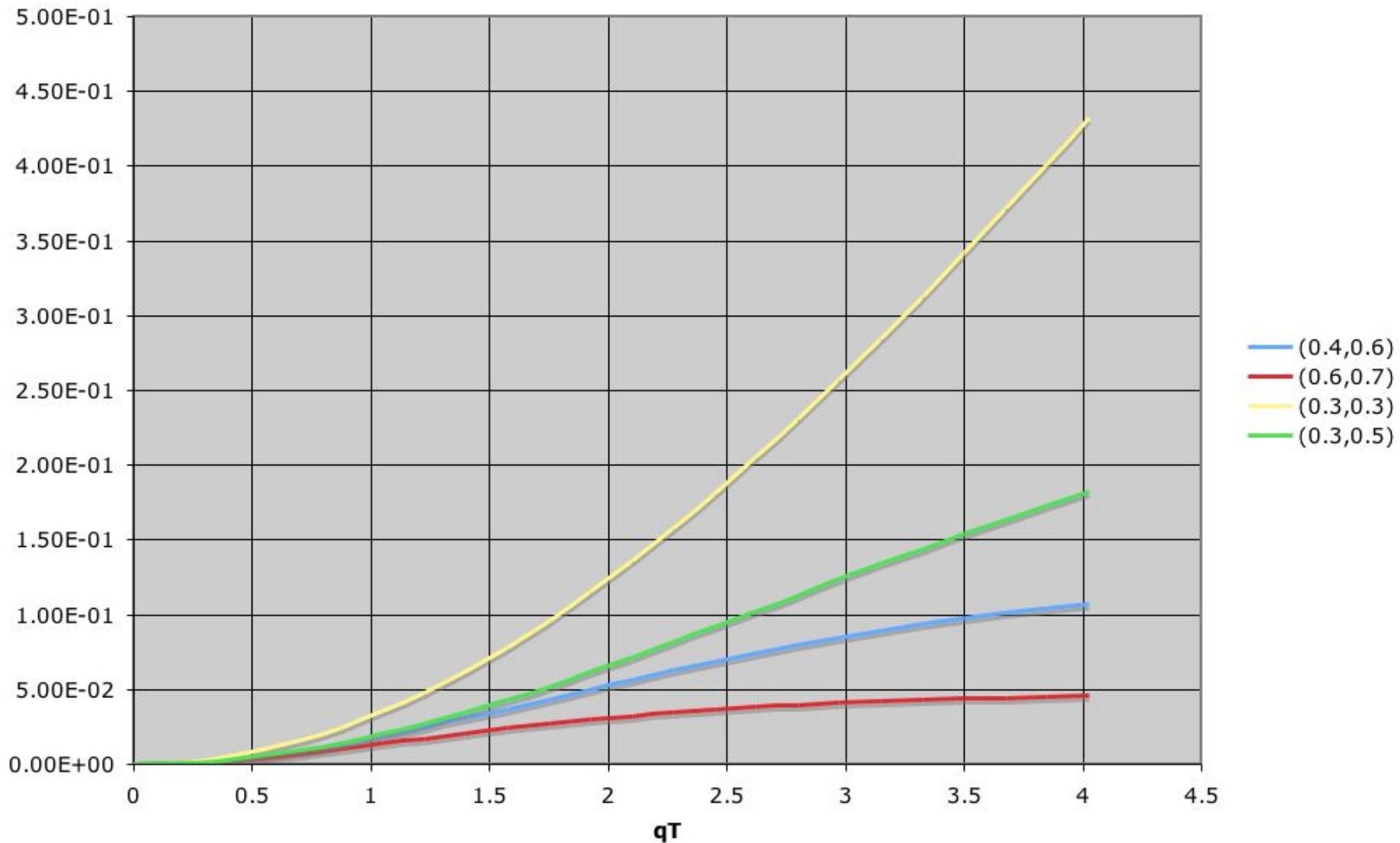
$n = (n^-, n^+, 0)$ (see CS NPB 1982, LG, Hwang, Metz, Schlegel PBL:2006)

- * *t*-channel cut vanishes
 - On Eikonal and Spectator
- * *s*-channel cut
 - On Fragmenting quark and gluon contributes
Reciprocity Fails, “T-odd” Fragmentation Function Universal between e^+e^- and SIDIS

Bacchetta, L.G., Goldstein, Mukherjee
Re-analysis and Kaons

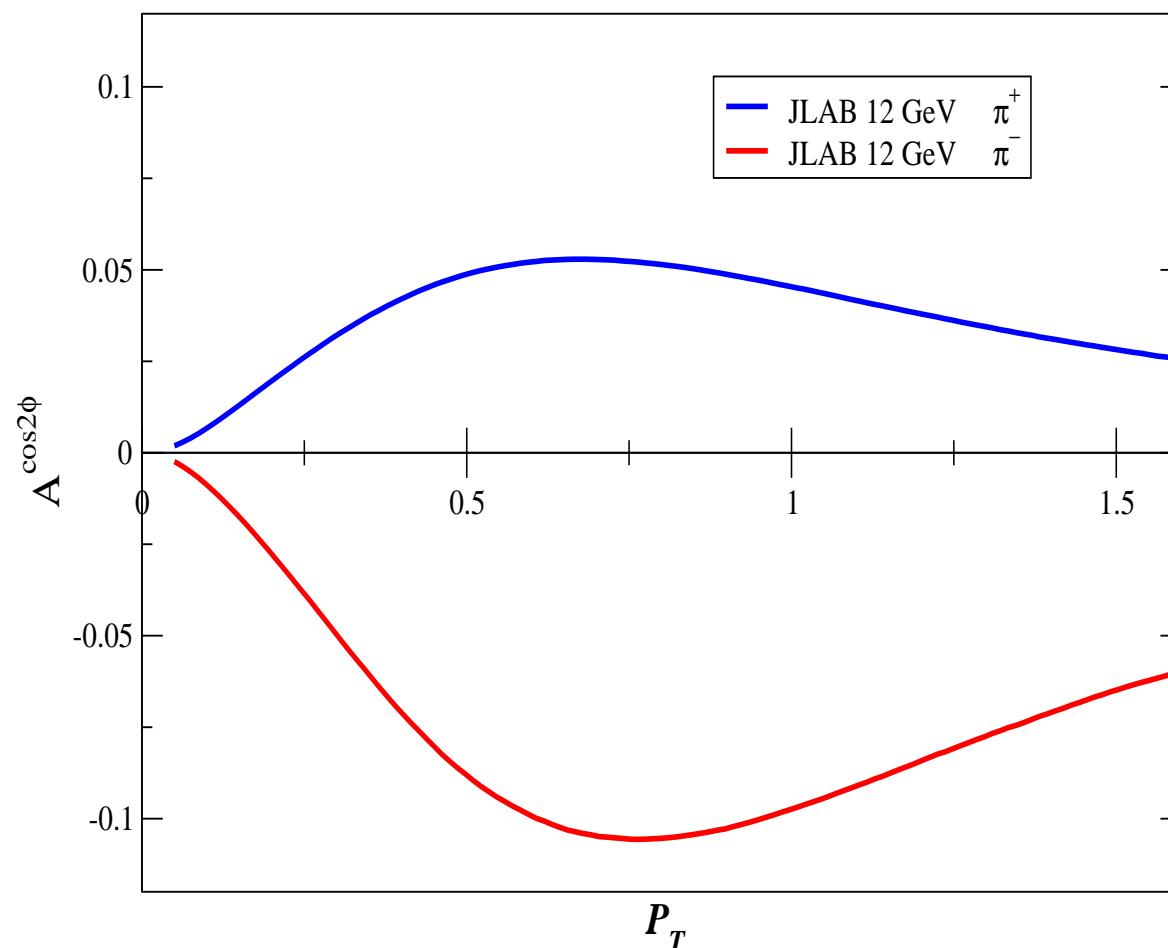


a0 for (z1,z2)

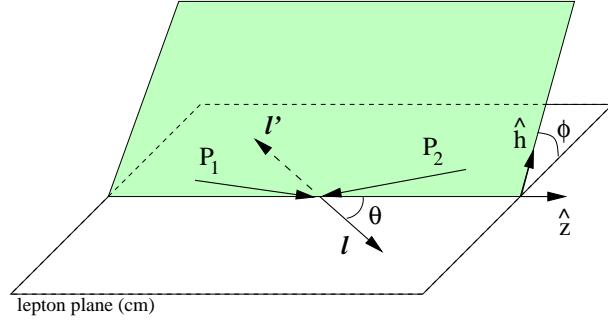


CLAS12 PAC 30-Avakian, Meziani. . . L.G. . .

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



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



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

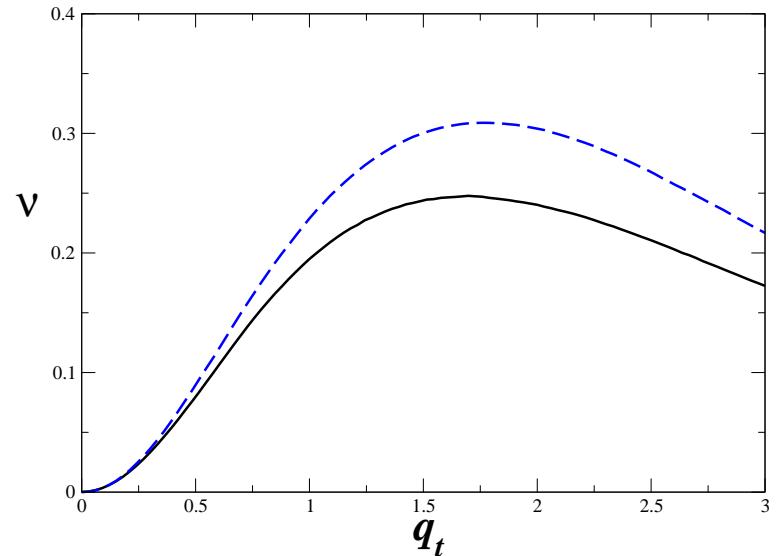
Boer PRD: 1999, Boer, Brodsky, Hwang PRD: 2003, L.G., Goldstein 2005

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

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

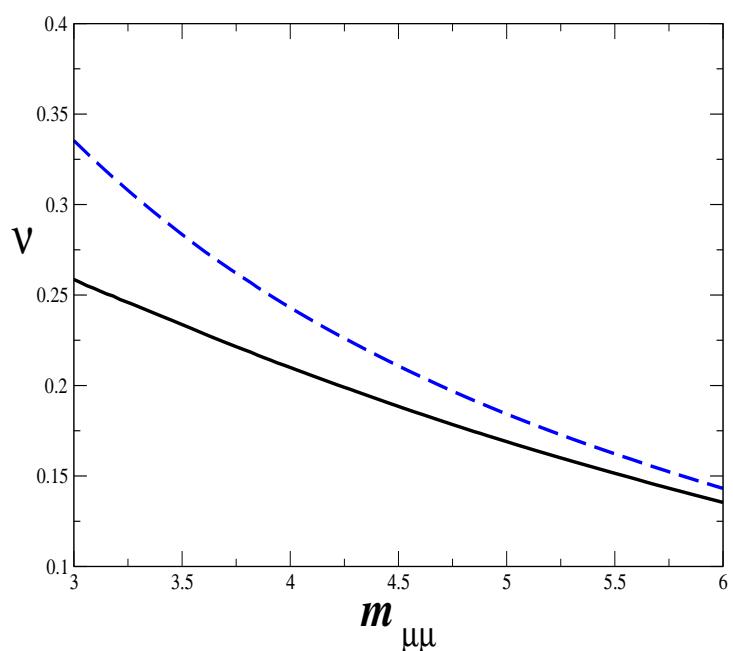
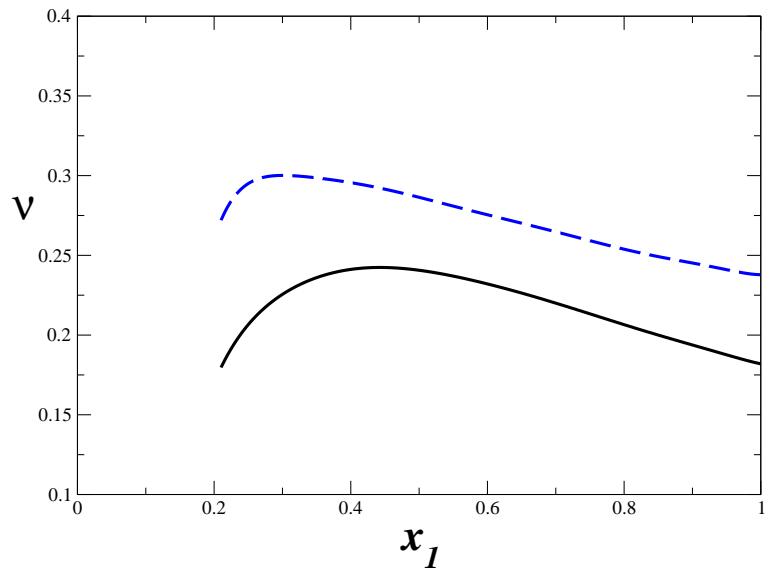
- Higher twist comes in Collins Soper PRD: 1977

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



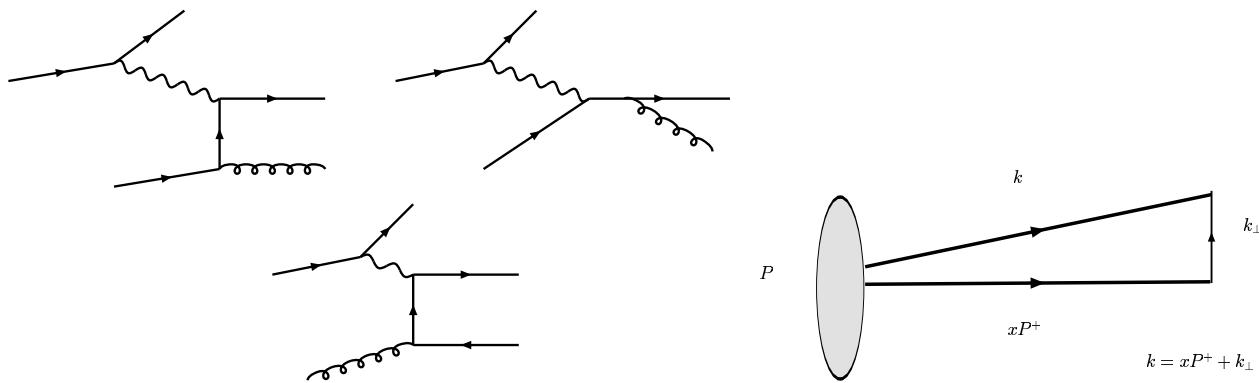
Perform Convolution integral L.G., Goldstein
 $s = 50 \text{ GeV}^2$, $x = [0.2 - 1.0]$,
 $q = [3.0 - 6.0] \text{ GeV}$, $q_T = 0 - 2.0 \text{ GeV}$

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

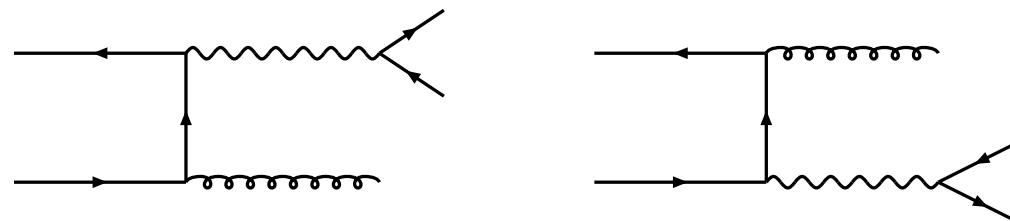


cos 2 ϕ JLAB, EIC, GSI, JPARC ...

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



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 possess terms of correlations between transverse momentum and transverse spin in QCD hard scattering
- The transversity 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