"Transverse Quark Spin Effects in Azimuthal Asymmetries-SIDIS and Drell Yan"

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Penn State Berks

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- Remarks Transverse Spin effects in TSSAs and AAs in QCD
- ⋆ Reaction Mechanisms: Colinear-limit ETQS-Twist Three, Beyond Co-linearity BHS-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)

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, $|\perp/\top>=\frac{1}{\sqrt{2}}(\,|+>\pm i|->\,)$

$$\Rightarrow A_N = \frac{d\hat{\sigma}^{\perp} - d\hat{\sigma}^{\top}}{d\hat{\sigma}^{\perp} + d\hat{\sigma}^{\top}} \sim \frac{2\,Im\,f^{*+}f^{-}}{|f^{+}|^2 + |f^{-}|^2}$$

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

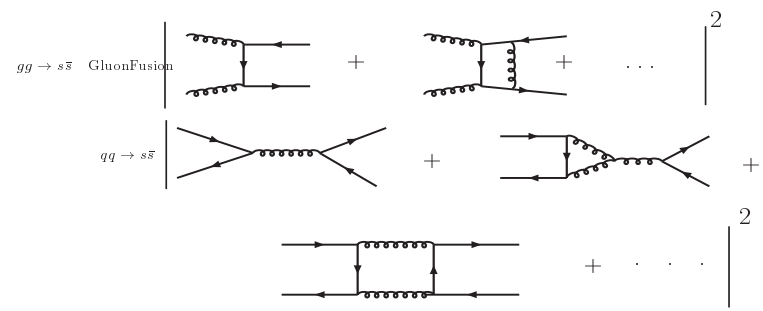
- Massless QCD conserves helicity & Born amplitudes are real!

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

Inclusive Λ Production Coliner QCD ($pp \to \Lambda^{\uparrow} X$) Dharmartna & Goldstein PRD 1990

- Need strange quark to polarize a Λ

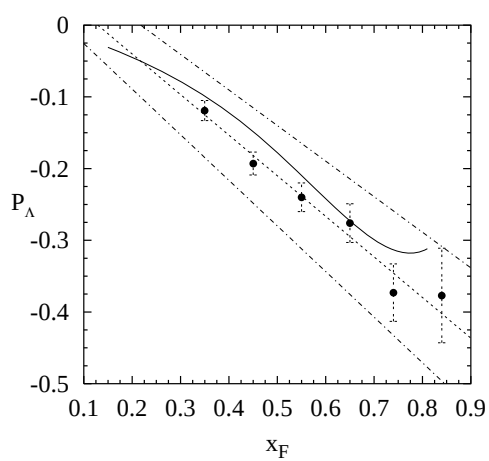
$$P_\Lambda = \frac{d\sigma^{pp\to\Lambda^{\uparrow}X} - d\sigma^{pp\to\Lambda^{\downarrow}X}}{d\sigma^{pp\to\Lambda^{\uparrow}X} + d\sigma^{pp\to\Lambda^{\downarrow}X}}$$

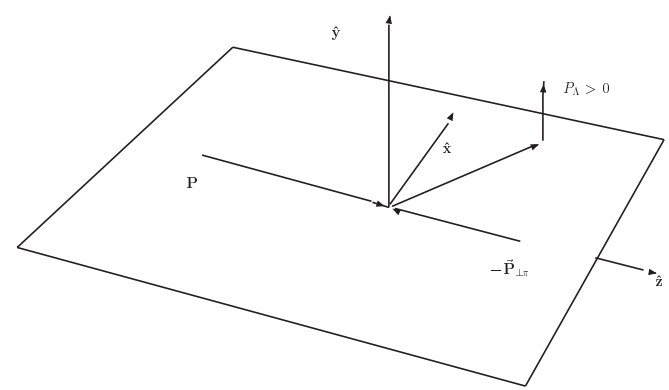


Phases generated through interference of loops and tree level

- Polarization $P_\Lambda \sim m_s \alpha_s / P_T$ twist 3 & small $\approx 5\%$ as generically stated
- Experiment *glaringly at odd with this result*

P_Λ in $p - p$ scattering-Fermi Lab



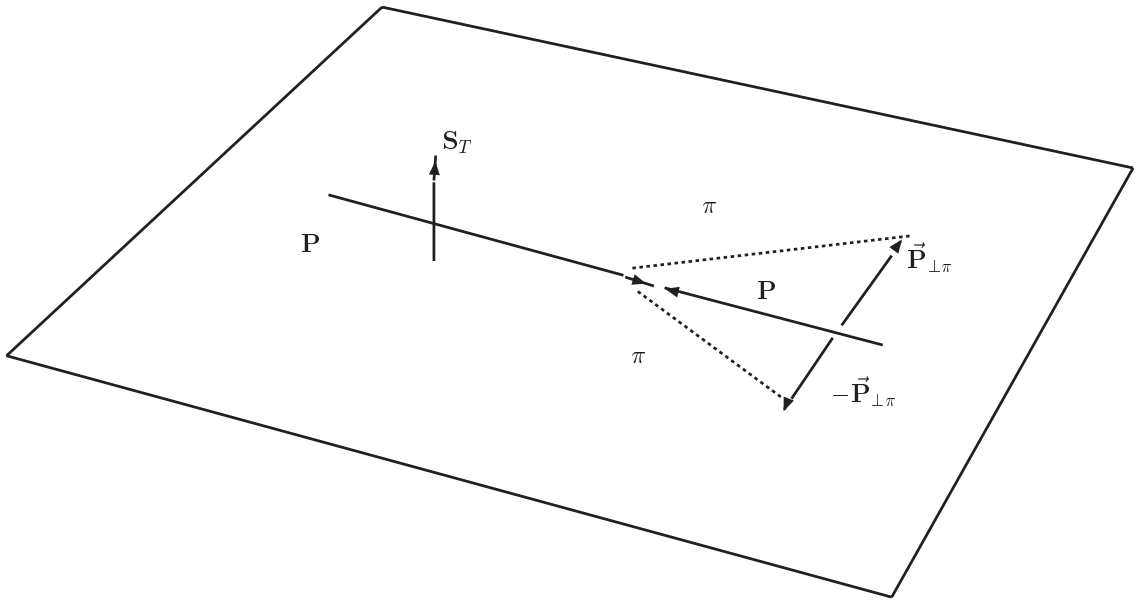


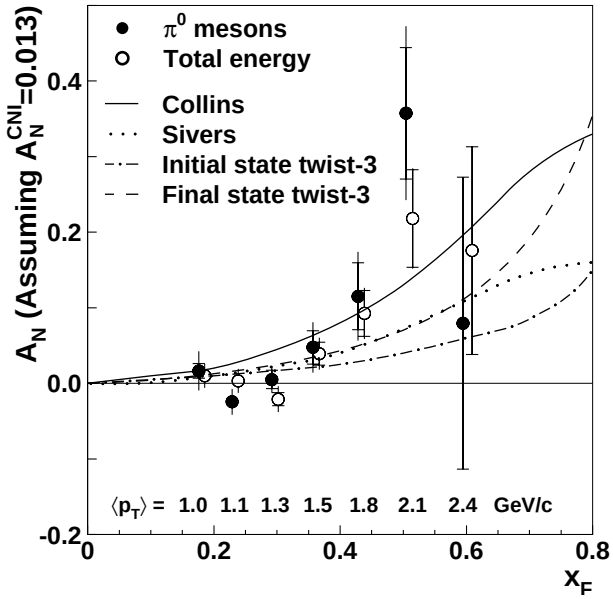
Heller,...,Bunce PRL:1983 Up-down asymmetry depicted for Λ production in $p - p$ COM-frame

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

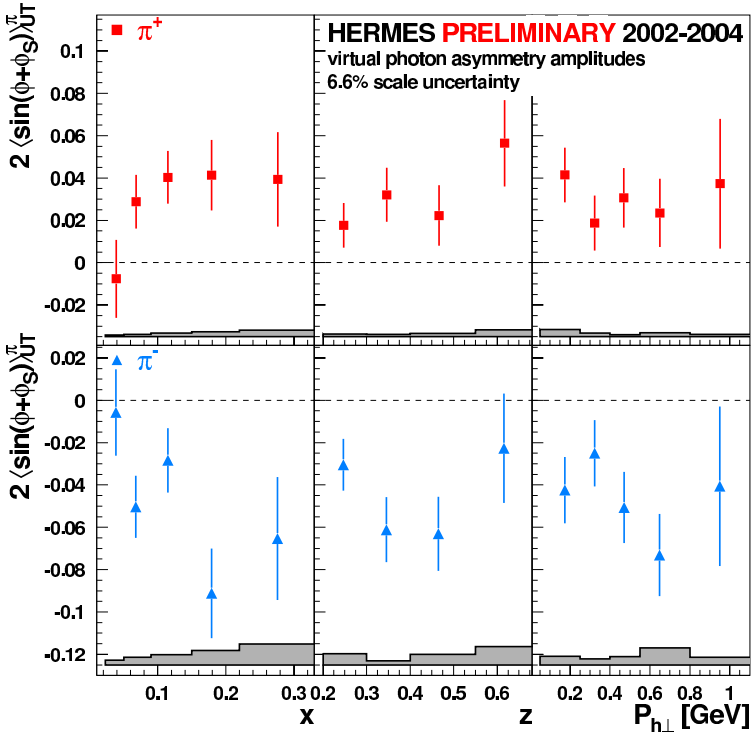
L-R asymmetry of π production and A_N for π_0 production at STAR : PRL 2004

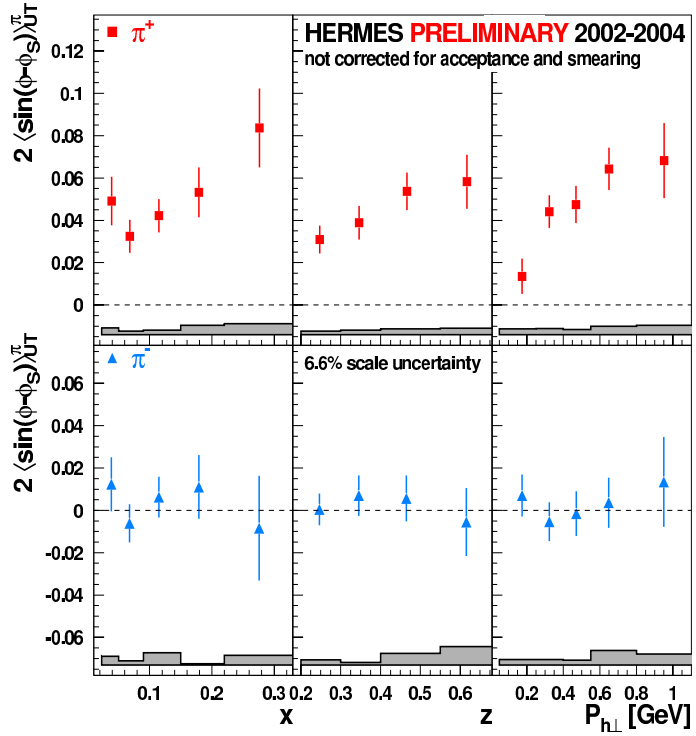
$$A_N = \frac{d\sigma^{p^{\uparrow}p\to\pi\ X} - d\sigma^{p^{\downarrow}p\to\pi\ X}}{d\sigma^{p^{\uparrow}p\to\pi\ X} + d\sigma^{p^{\downarrow}p\to\pi\ X}}$$



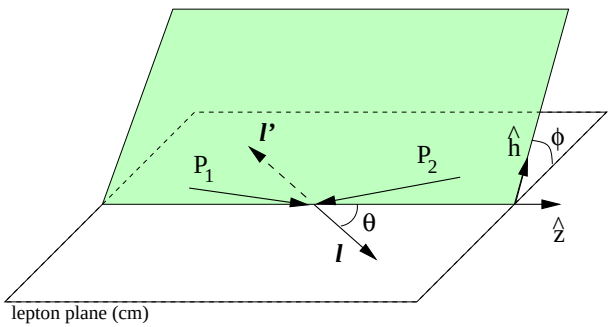


HERMES SIDIS $e\, p^{\uparrow} \to \pi\, X$



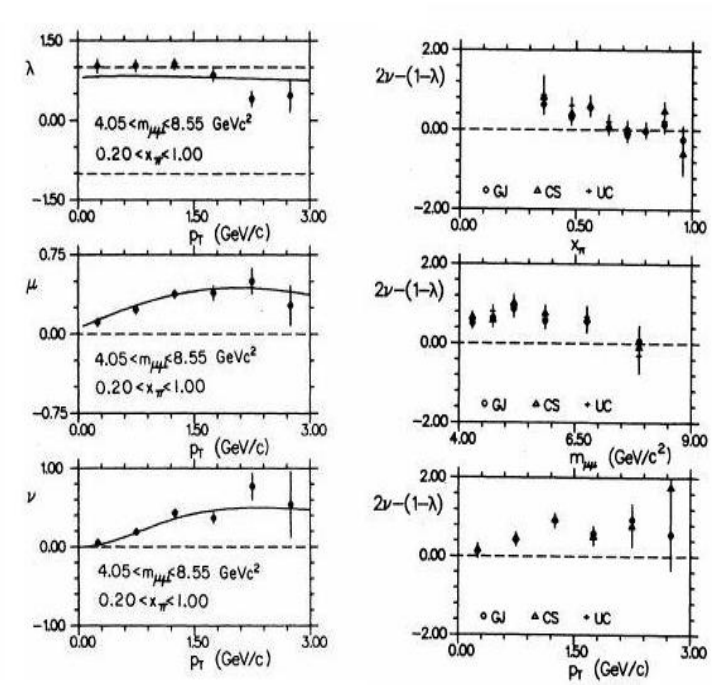


Azimuthal Asymmetry in Unpolarized DRELL YAN $\cos 2\phi$



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

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



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

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

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

NNLO QCD predict Lam-Tung relation, $1-\lambda-2\nu=0$ (Mirkes Ohnemus, PRD 1995)

As well, *unexpected large* $\cos 2\phi$ $\nu \sim 10-30\%$ AA

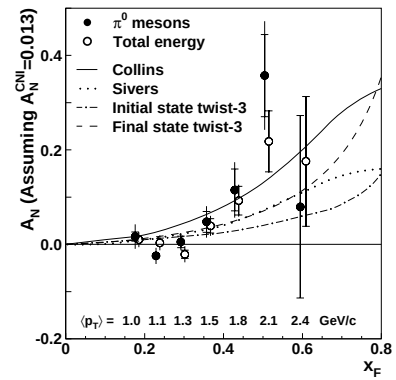
ETQS-Twist Three Mechanism @ Lg $P_T > \Lambda_{qcd}$

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

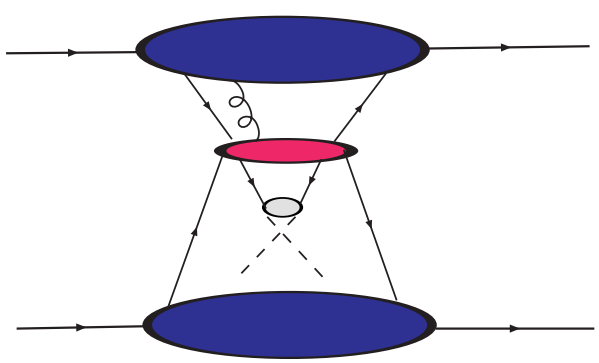
A_N twist three yet phases generated in co-linear QCD from gluonic and fermionic poles in propagator of hard parton subprocess Efremov & Teryaev :PLB 1982

Get helicity flips and phases, $m_q \to\sim M_H$ and $\alpha_s \to \sqrt{\alpha_s}$

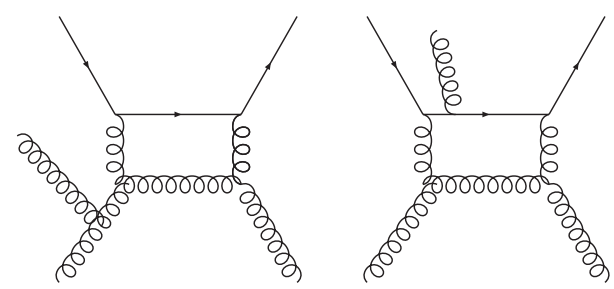
$$\frac{1}{x+s\pm i\epsilon} = P\frac{1}{x-s} \mp i\pi\delta(x-s)$$



- Factorized co-linear QCD Qiu & Sterman :PLB 1991, 1999, Koike & Kanazawa:PLB 2000, (talks by Vogelsang and Yuan on new work on ETQS Ji,Qiu,Vogelsang,Yuan:PR2006



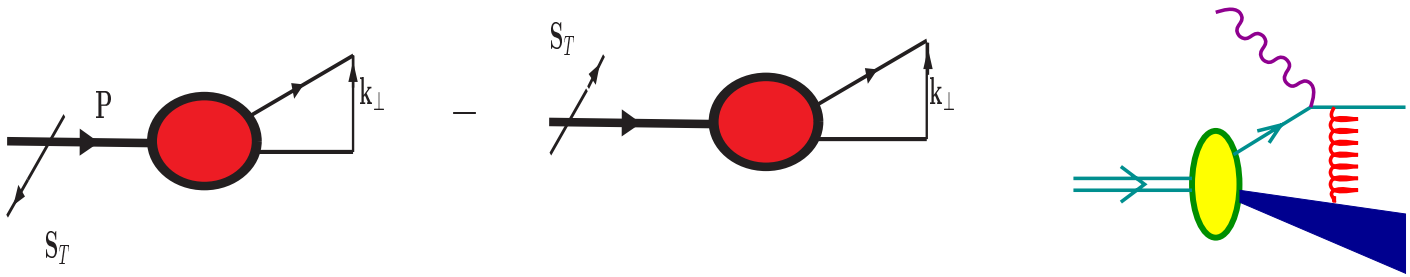
$\Rightarrow$



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

- Sensitivity to $\boldsymbol{k}_\perp$ intrinsic quark momenta, associated **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, Anselmino & Murgia PLB: 1995 Correlation accounts for left-right TSSA in $P\,P^\perp \to \pi\,X$



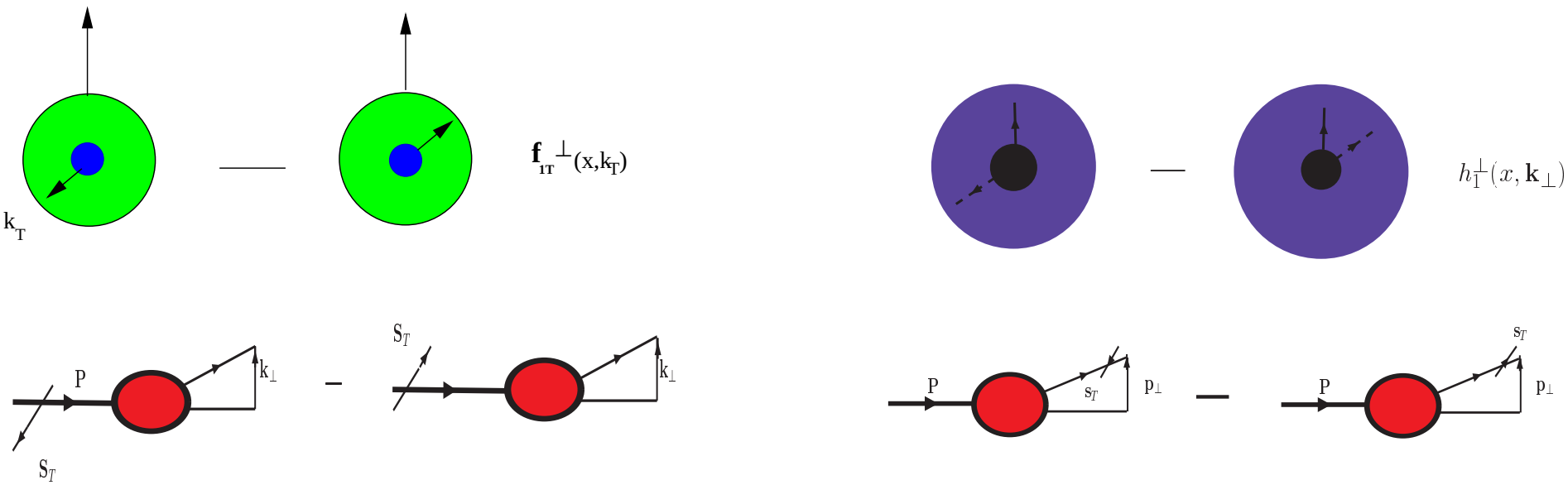
- SIDIS w/ transverse polarized nucleon target $e\,p^\perp \to \pi X$
  $i\boldsymbol{S}_T \cdot (\boldsymbol{P} \times \boldsymbol{k}_\perp) \to f_{1T}^\perp(x, \boldsymbol{k}_\perp)$
  Brodsky, Hwang, Schmidt PLB: 2002 FSI produce necessary phase for TSSAs-*Leading Twist*
  Ji, Yuan PLB: 2002, Boer, Piljman, Mulders: NPB 2003 -Sivers fnct. FSI emerge from Color Gauge-links

- Collins NPB 1993 "T-odd" correlation of transversely polarized fragmenting quark:
  TSSA in lepto-production $i\boldsymbol{s}_T \cdot (\boldsymbol{p} \times \boldsymbol{P}_{h\perp}) \to H_1^\perp(z, \boldsymbol{p}_\perp)$
  $\boldsymbol{s}_T$ 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

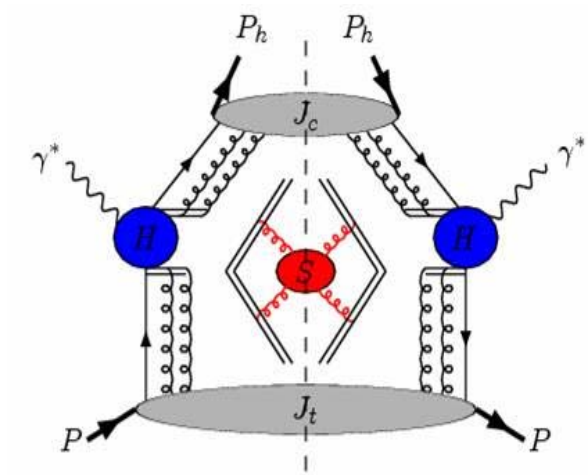
Boer and Mulders PRD: 1998 "T-odd" correlation of transversely polarized *quark spin* with it's intrinsic $\boldsymbol{k}_\perp$ $i s_T \cdot (\boldsymbol{k} \times \boldsymbol{P}) \rightarrow h_1^\perp(x, \boldsymbol{k}_\perp)$

Boer PRD: 1999-$\cos 2\phi$-AA in unpolarized lepto-production $e\,P \rightarrow e'\,\pi\,X$ and "DY" $\pi^- + p \rightarrow \mu^+ + \mu^- + X$ or $\bar{p} + p \rightarrow \mu^-\mu^+ + X$ (latter is cleaner, no Fragmentation)



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

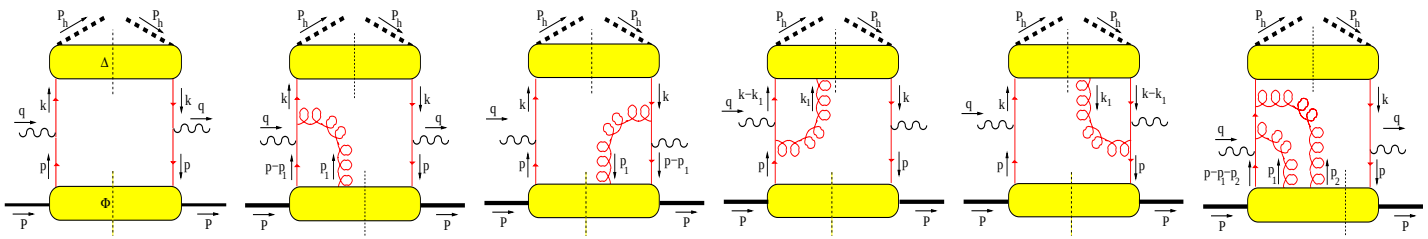
Ji, Ma, Yuan: PLB, PRD 2004, 2005 building on work of Collins-Soper NPB: 81, extended factorization theorems to 1-loop and beyond



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

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

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

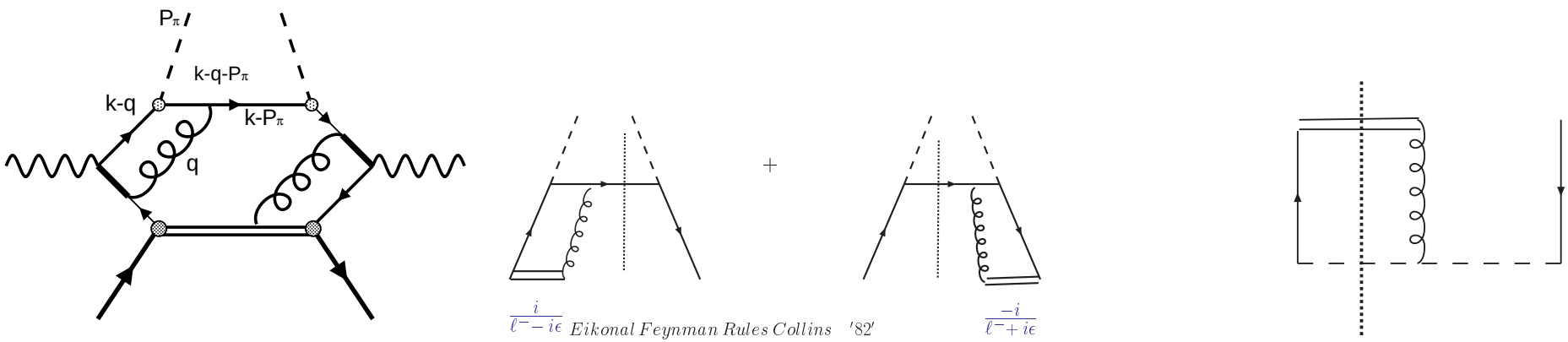
$$\Phi(x,\boldsymbol{p}_\perp)=\frac{1}{2}\{f_1(x,\boldsymbol{p}_\perp)\,\not{n}_+ + h_1^\perp(x,\boldsymbol{p}_\perp)\frac{\sigma^{\alpha\beta}p_{T\alpha}n_{+\beta}}{M} + f_{1T}^\perp(x,\boldsymbol{p}_\perp)\frac{\epsilon^{\mu\nu\rho\sigma}\gamma^\mu n_+^\nu p_\perp^\rho S_T^\sigma}{M}\cdots\}$$

<u>SIDIS cross section</u>

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

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

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



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

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

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

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 and Ji-Yuan point-like nucleon-quark-diquark vertex, logarithmically divergent asymmetries, Goldstein, L.G., ICHEP 2002; hep-ph/0209085, L.G., Goldstein, Oganessyan PRD 2003; Boer, Brodsky, Hwang, PRD: 2003(Drell-Yan)

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

- 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)

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

with

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

Sign of Boer Mulders Function
GPDs and correlations transverse-spin & intrinsic $k_\perp$

- Connection Sivers effect/function with anomolus magnetic moment of quark-q
  $\kappa^q \leftrightarrow f_{1T}^{\perp(q)}$
  $d_y^q = \int dx \int d^2\mathbf{b}_\perp q_X(x, \mathbf{b}_\perp) b_y = \kappa^q/2M$
  - ⋆ Serves to fix sign of Sivers function

- As well $\kappa_T^q \leftrightarrow h_1^{\perp q}$
  $d_y^q = \int dx \int d^2\mathbf{b}_\perp \delta q^X(x, \mathbf{b}_\perp) b_y = \kappa_T^q/2M$

  - ⋆ Serves to fix sign of Boer Mulders function
- Yeilds *transverse distortion* in impact parameter space of transversly polarized quarks in an unpolarized nucleon Burkardt PRD 2005, Diehl, Hägler EPJC 2005

⋆ This result implies that the up and down quark Boer Mulders function are same sign.

- Supports
  - ⋆ Lg N_C arguments Pobylitsa hep-ph/0301236
  - ⋆ Bag Model calculation of Feng Yuan PLB 2003
  - ⋆ 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

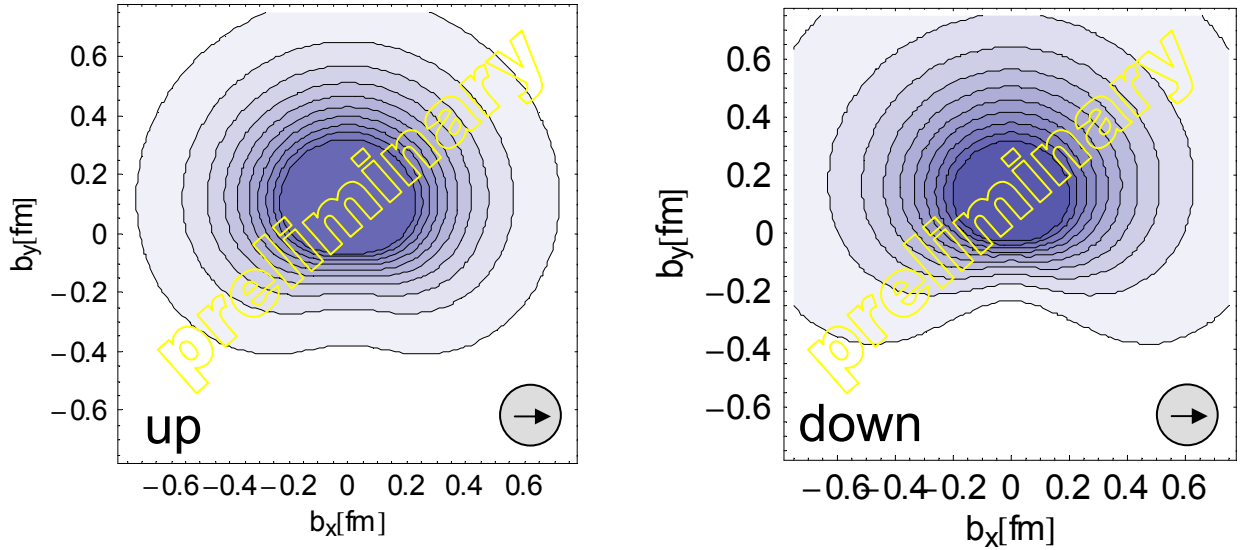
$$f_{1Tq}^{\perp}(x,p_{\perp}) \sim -\int dx E_q(x,0,0) = -B_{10,q}(0) = -\kappa_q$$

Burkardt PRD 2005

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

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

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

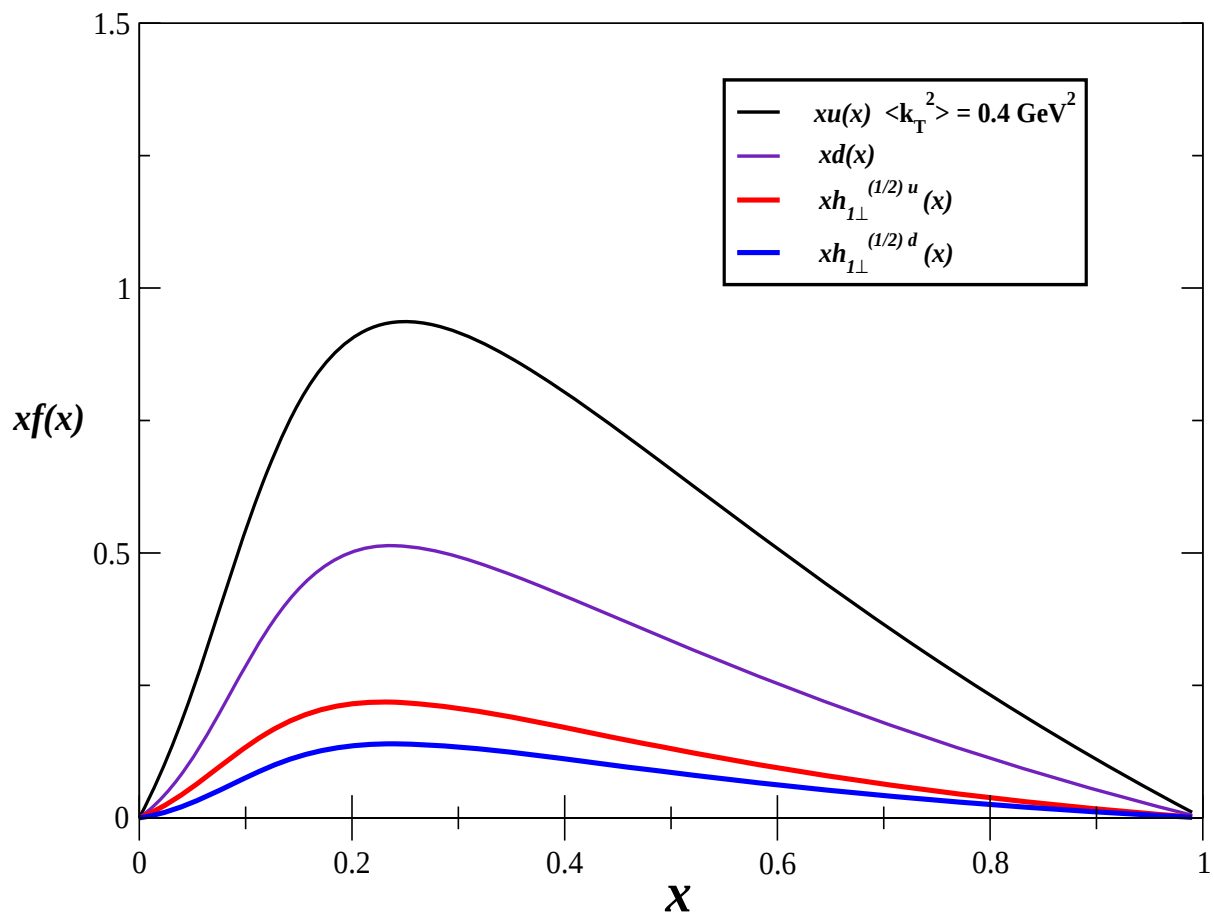


could imply to sizeable Boer-Mulders-effect

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,
  $\gamma_5(\gamma^\mu + P^\mu/M)$

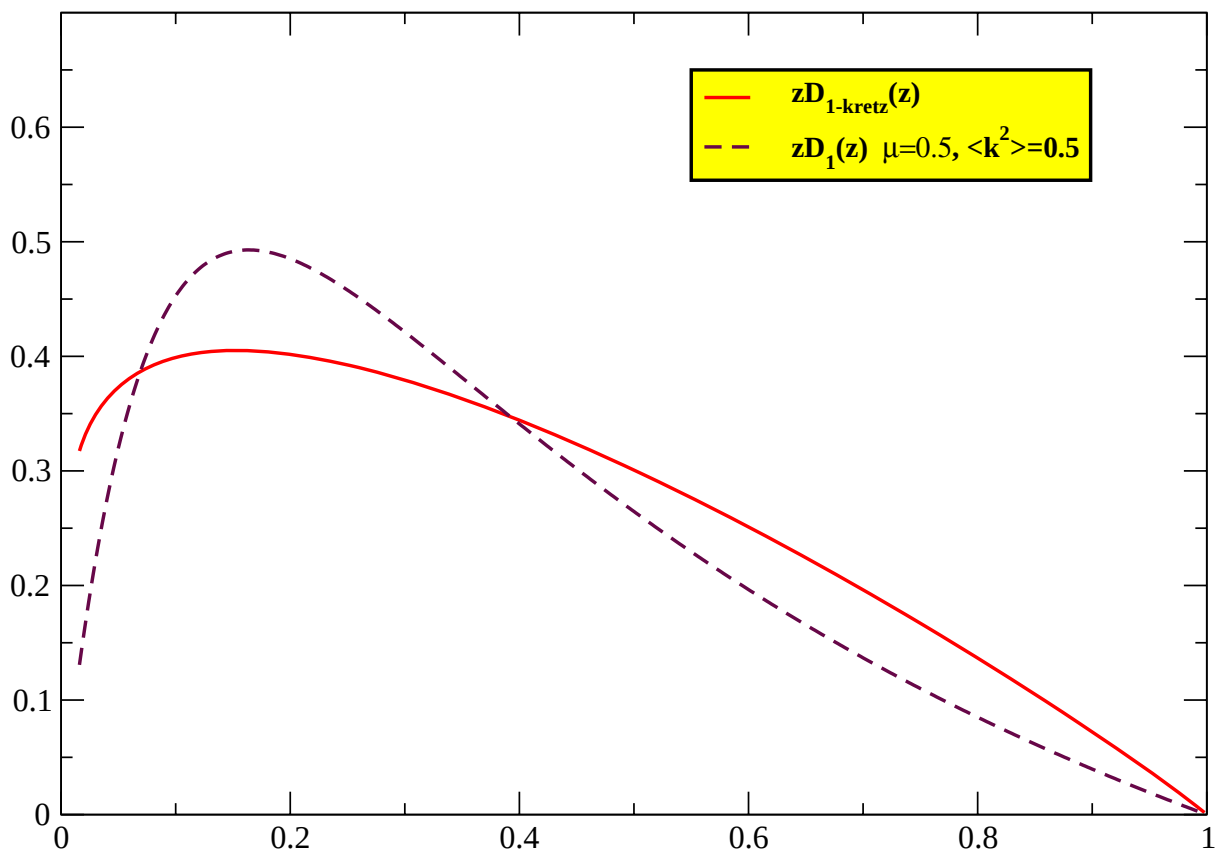


PRELIMINARY

Pion Fragmentation Function

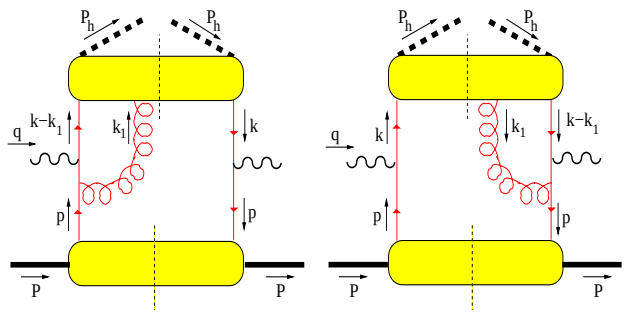
$$D_1(z) \quad = \quad \mathcal{N}' \frac{(1-z)}{z^2} \Big\{ \frac{m^2 - \Lambda'(0)}{\Lambda'(0)} - \Big[2b' \Big(m^2 - \Lambda'(0) \Big) - 1 \Big] \, e^{2b'\Lambda'(0)} \Gamma(0, 2b'\Lambda'(0)) \Big\},$$

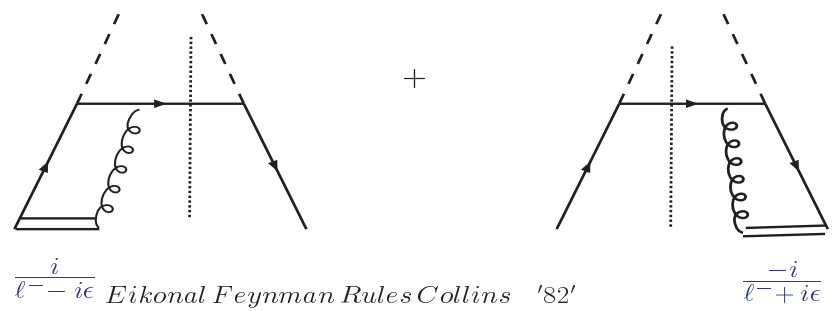
which, multiplied by z at $< k_\perp^2 >= (0.5)^2$ GeV^2 and $\mu = m$, estimates the distribution of Kretzer, PRD: 2000



Gauge Link-Pole Contribution to T-Odd Collins Function

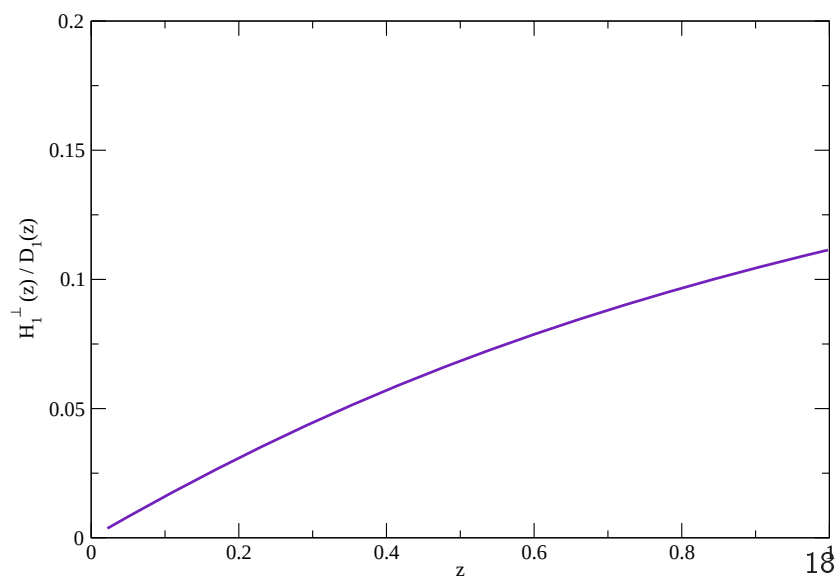
L.G.,Goldstein,Oganessyan PRD68,2003 $\Delta^{[\sigma^{\perp -}\gamma_5]}(z,k_\perp) = \frac{1}{4z}\int dk^+ Tr(\gamma^-\gamma^\perp\gamma_5\Delta)|_{k^-=P_\pi^-/z}$





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

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



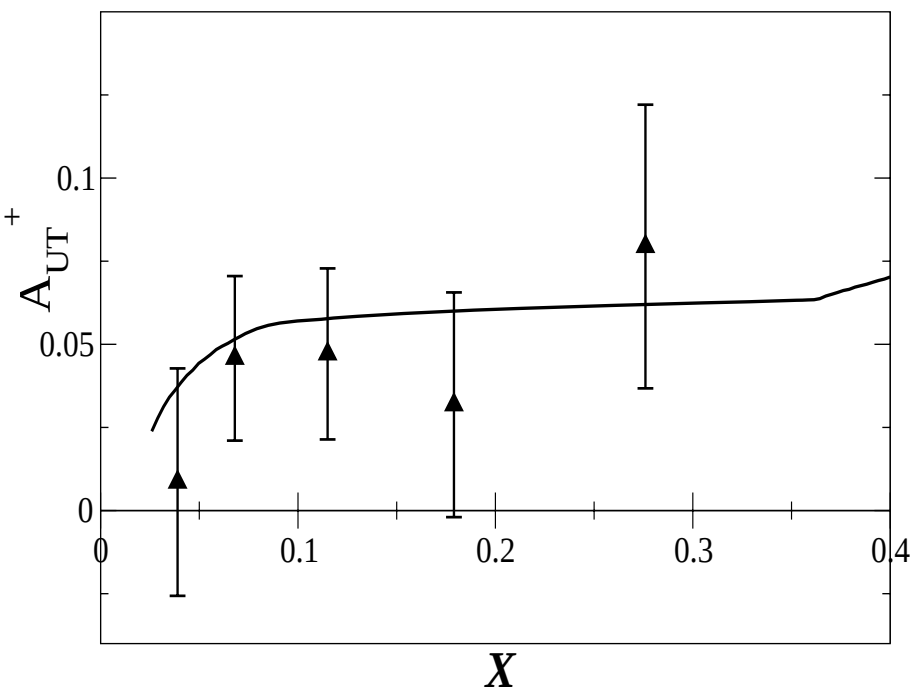
Collins Asymmetry

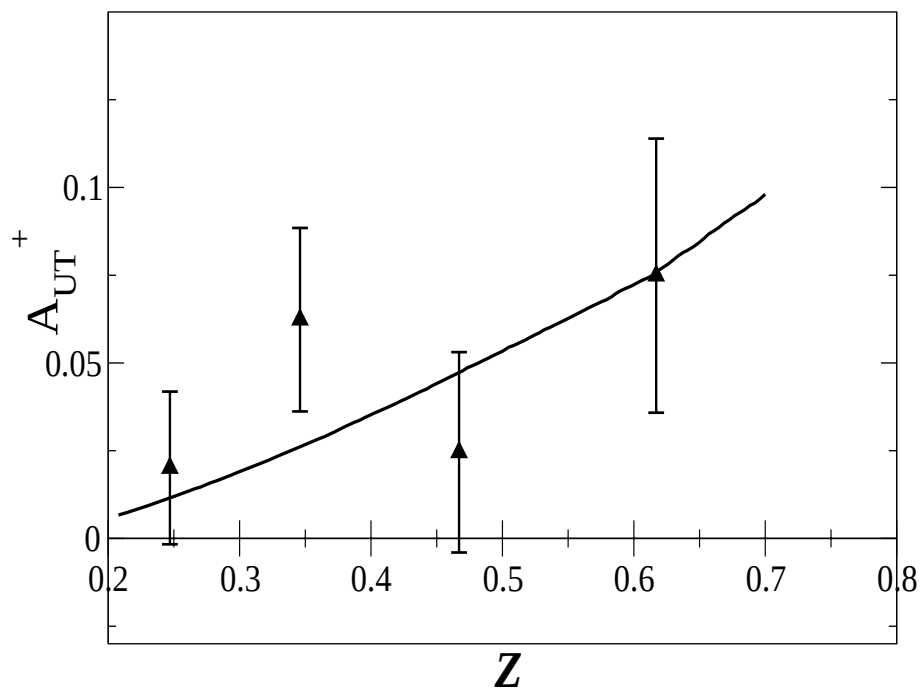
L.G., Goldstein, Oganessyan PRD 2003: updated For the HERMES kinematics

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

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

Data from A. Airapetian et al. PRL94,2005

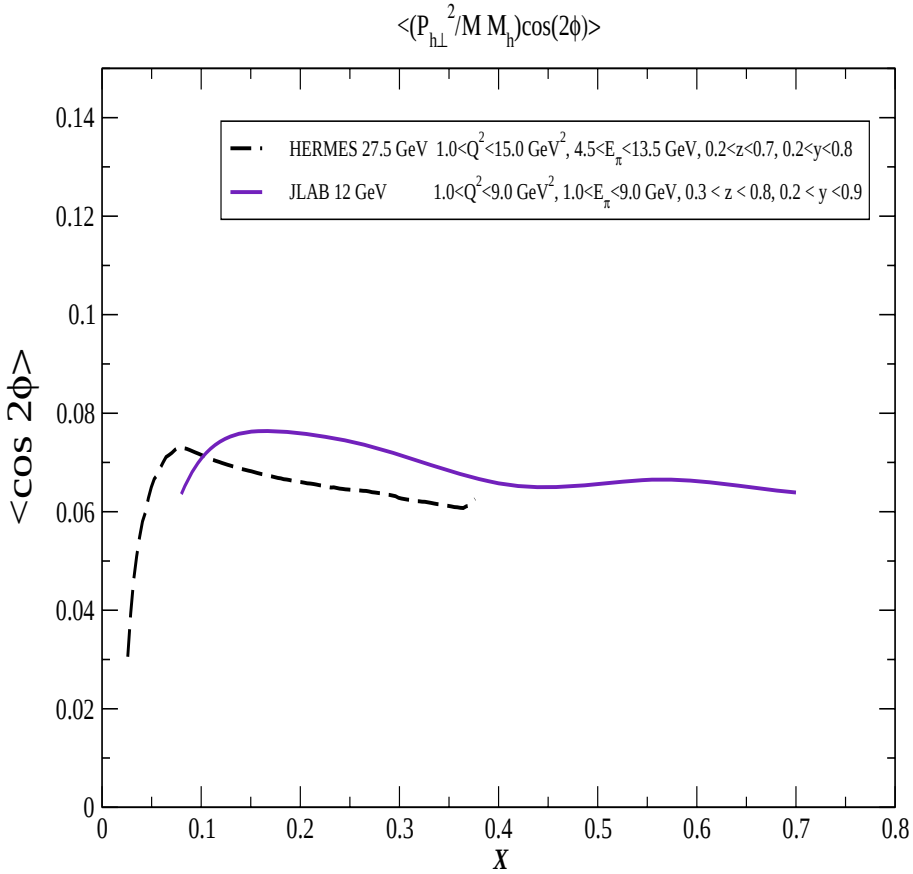


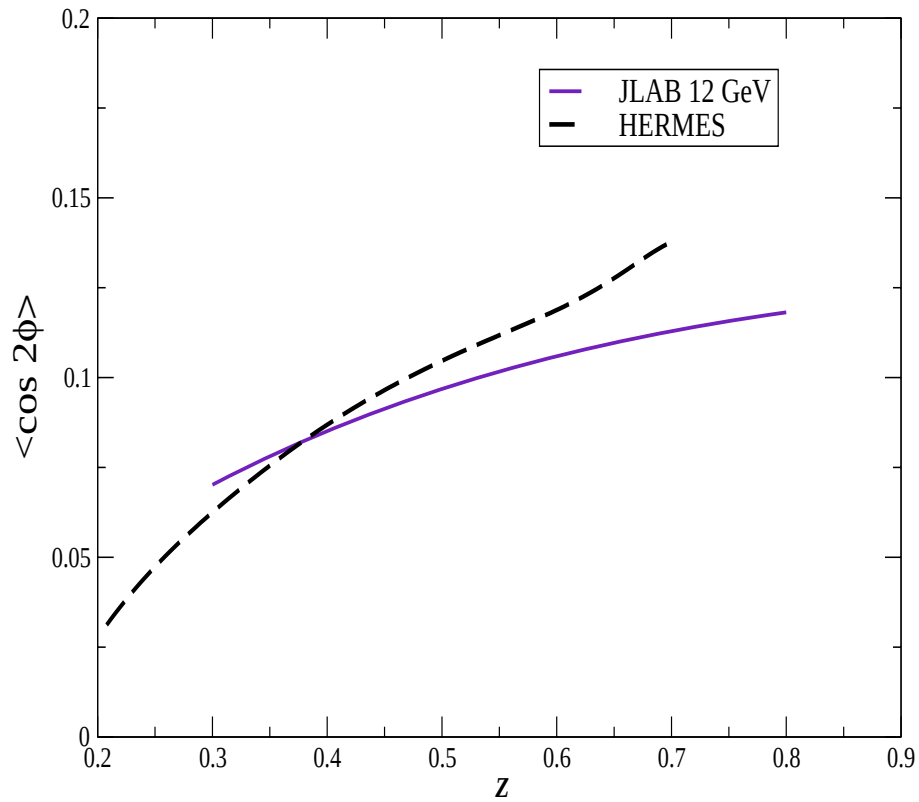


T-odd $\cos 2\phi$ asymmetry

Transversity of quarks inside an unpolarized hadron, $\cos 2\phi$ SIDIS D. Boer, P. Mulders, PRD: 1998

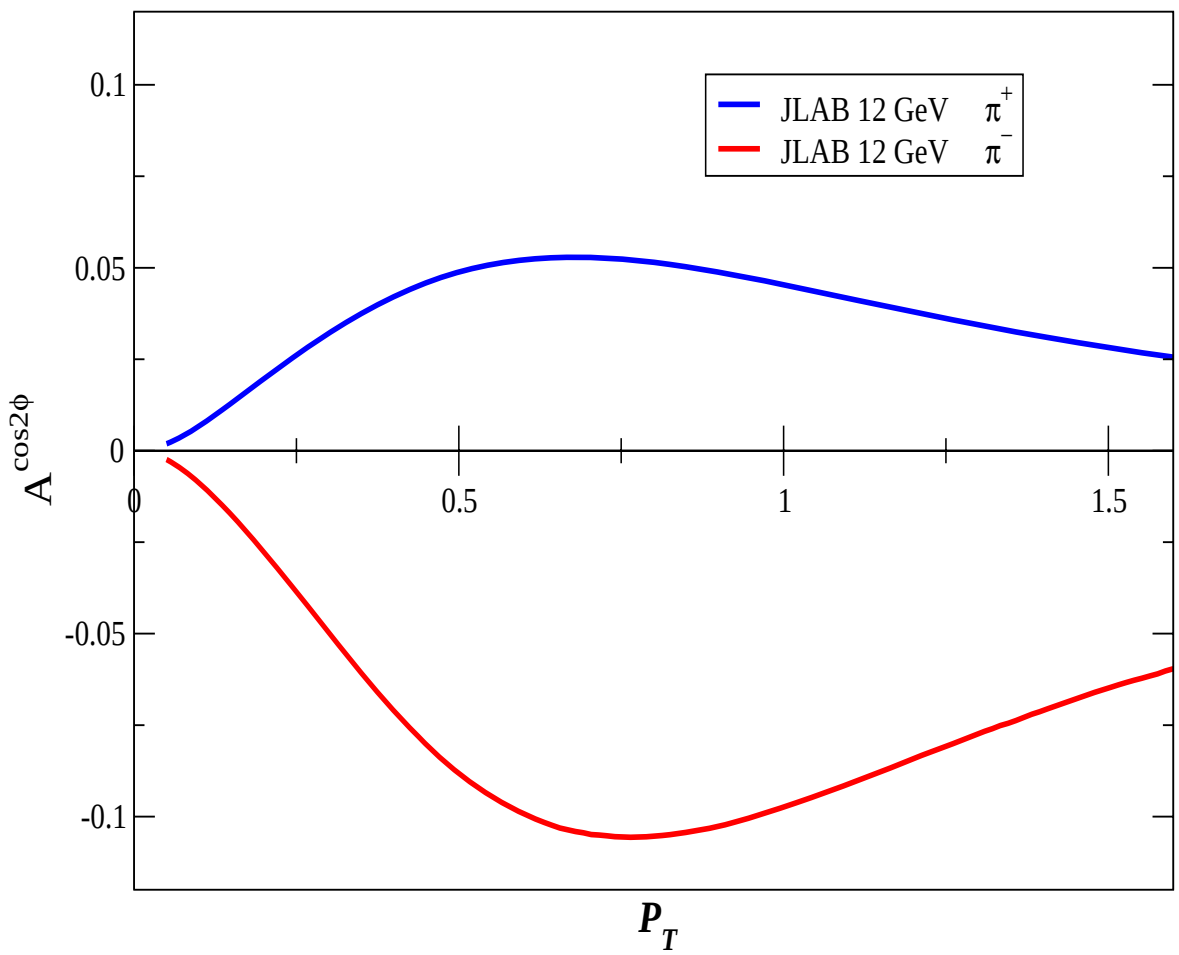
$$\langle \frac{|P_{h\perp}^2|}{MM_h} \cos 2\phi \rangle_{UU} = \frac{\int d^2P_{h\perp} \frac{|P_{h\perp}^2|}{MM_h} \cos 2\phi \, d\sigma}{\int d^2P_{h\perp} \, d\sigma} = \frac{8(1-y) \sum_q e_q^2 h_1^{\perp(1)}(x) z^2 H_1^{\perp(1)}(z)}{(1+(1-y)^2) \sum_q e_q^2 f_1(x) D_1(z)}$$



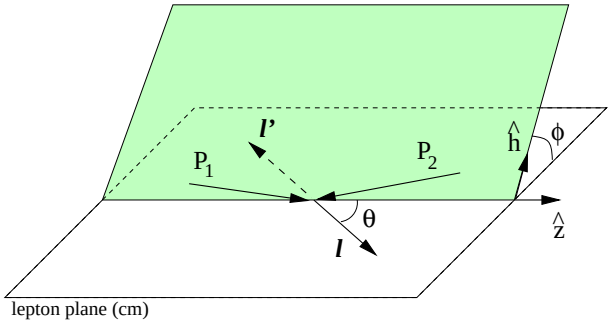


CLAS12 PAC 30-Avakian, Meziani. . . L.G. . .

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



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



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

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

Angle-lepton pair orientation in their COM frame relative and the initial hadron's plane.

Boer PRD: 1999, Boer, Brodsky, Hwang PRD: 2003

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

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

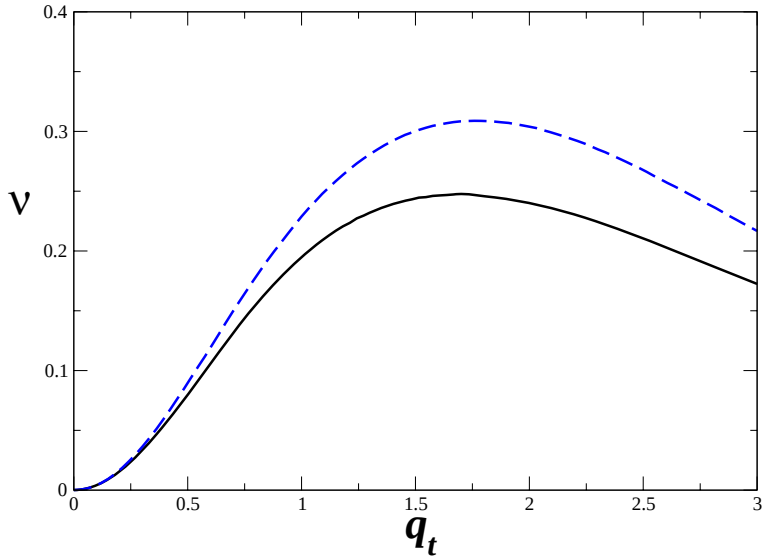
- Higher twist comes in Collins SoperPRD: 1977

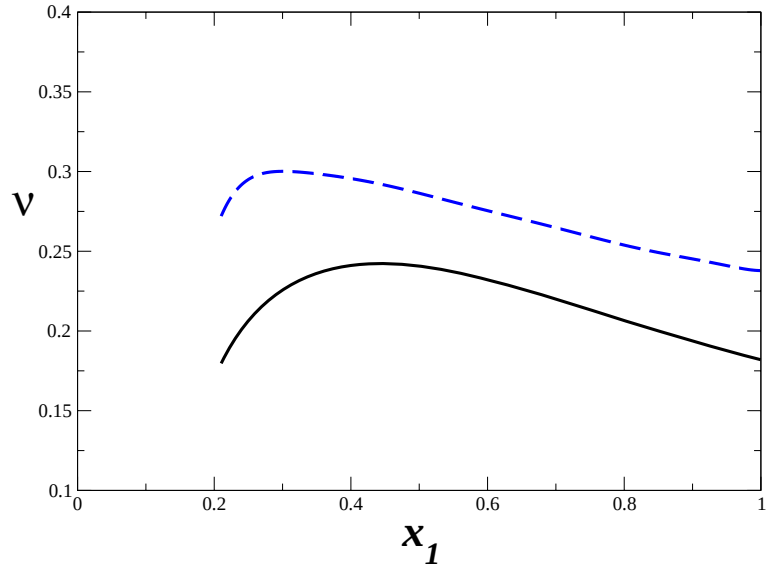
$$\nu = \frac{2\sum_a e_a^2 \mathcal{F}\left[(2\boldsymbol{p}_\perp \cdot \boldsymbol{k}_\perp - \boldsymbol{p}_\perp \cdot \boldsymbol{k}_\perp)\frac{h_1^\perp(x,\boldsymbol{k}_T^2)\bar{h}_1^\perp(\bar{x},\boldsymbol{p}_T)}{M_1 M_2}\right] + \nu_4[w_4 f_1 \bar{f}_1]}{\sum_{a,\bar{a}} e_a^2 \mathcal{F}[f_1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

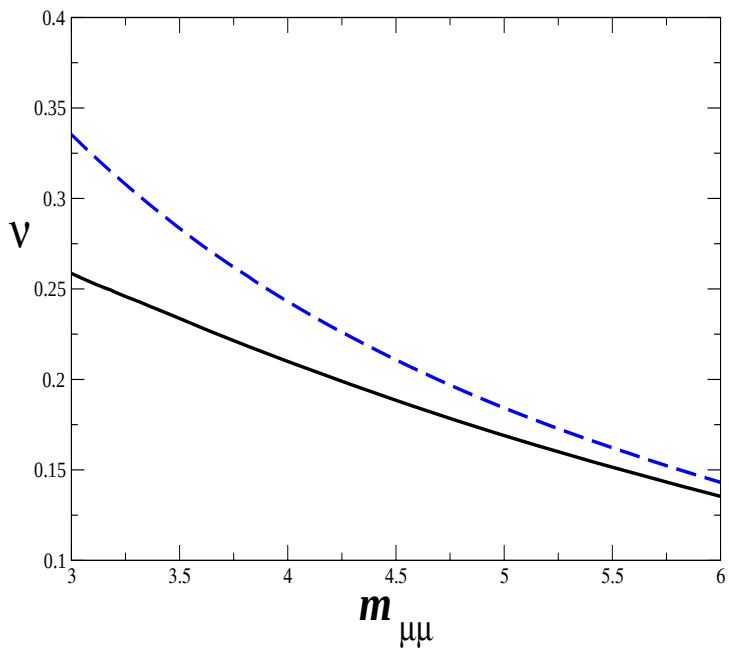
$$\nu_4 = \frac{\frac{1}{Q^2}\sum_a e_a^2 \mathcal{F}\left[w_4\, f_1(x,\boldsymbol{k}_\perp)\bar{f}_1(\bar{x},\boldsymbol{p}_\perp)\right]}{\sum_a e_a^2 \mathcal{F}\left(f_1(x,\boldsymbol{k}_\perp)\bar{f}_1(\bar{x},\boldsymbol{p}_\perp)\right)}$$

- Perform Convolution integral L.G., Goldstein hep-ph/0506127
  $s = 50\,GeV^2$, $x = [0.2 - 1.0]$, and $q = [3.0 - 6.0]\ GeV$, $\boldsymbol{q}_T = 0 - 2.0\,GeV$

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


ν
q_t


ν
x_1

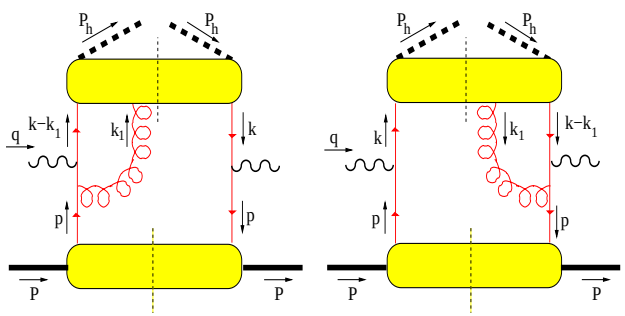

ν
$m_{\mu\mu}$

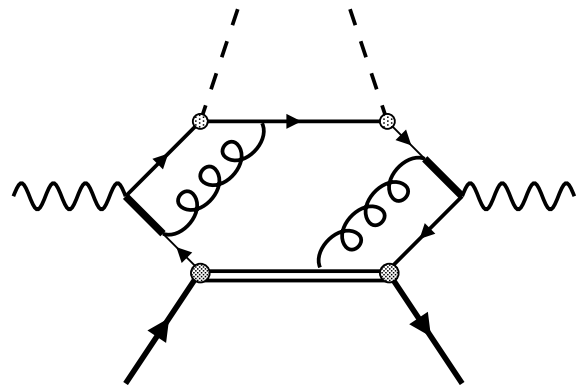
Gauge Link Contribution to Collins Function

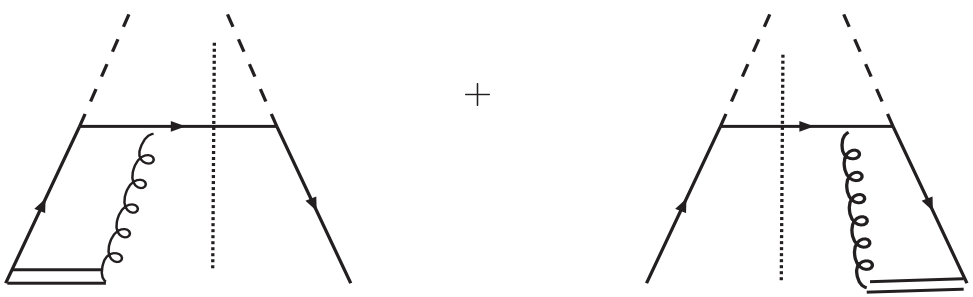
Metz: PBL 2002, L.G., Goldstein, Oganessyan PRD: 2003: Bacchetta, Metz, Jang: PLB: 2003, Amrath, et. al: PRD 2005,

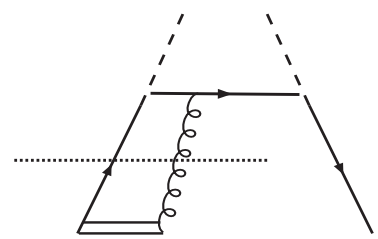
L.G., Goldstein in progress

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









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

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

- ⋆ 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

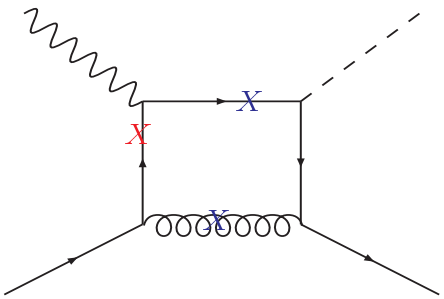
$$\frac{1}{n \cdot \ell \pm i\epsilon} \quad \cdots$$

$n = (n^-, n^+, 0)$ (see Collins Soper NPB 1982 Ji, Yuan, Ma PLB: 2004, LG, Hwang, Metz, Schlegel PBL:2006)

- ⋆ t-channel cut non-physical
  - On Fragmenting quark and gluon ⇒ equivalent to cut in S-channel
  - On Eikonal and Spectator ⇒ equivalent to cut in t-channel

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

S-Channel Cut-COMO Proceedings 2006



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

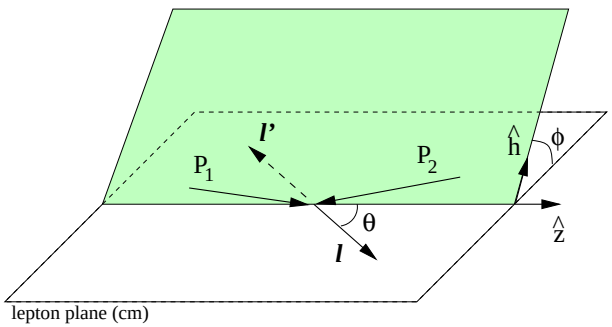
where

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

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

$P \equiv |\mathbf{P}_h|$ 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 $m \to 0$. Results depend the non-perturbative correlator mass μ.

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)

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

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

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.
- Along chiral odd transversity T-even distribution function, T-odd distribution and fragmentation functions provide an explanation for substantial asymmetries 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
- Address 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