“Transverse Quark-Spin Effects in SIDIS”

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Deep Inelastic Scattering 2007

- Remarks Transverse Spin effects in TSSAs and AAs in QCD
- ⋆ Reaction Mechanisms: Beyond Co-lineararity 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 $\cos 2\phi$ & $\sin 2\phi$ asymmetries in SIDIS
- Conclusions

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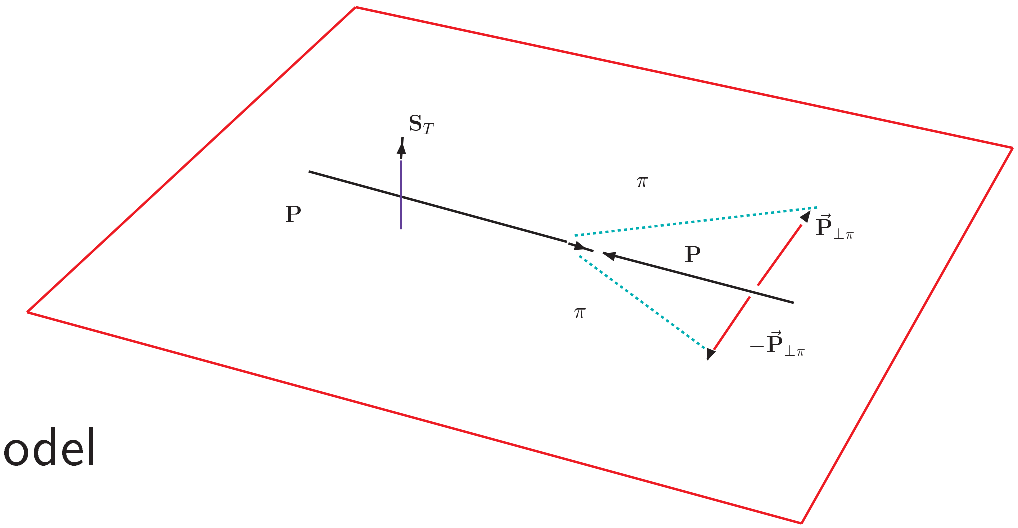
Transverse SPIN Observables
SSA (TSSA)

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



- ⋆ 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 $\hat{\sigma}$

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

- ⋆ Requires relative phase btwn helicity amps

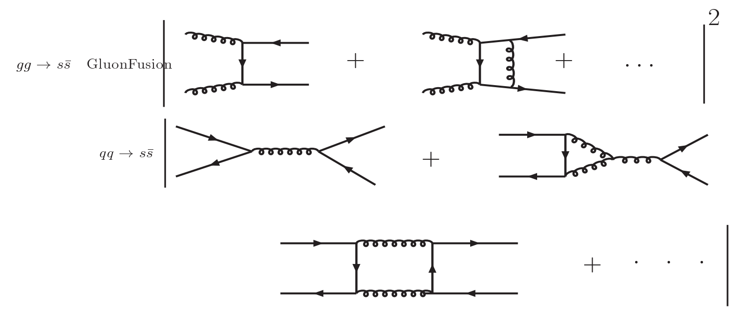
- QCD interactions conserve helicity $m_q \to 0$ & Born amplitudes real!

- ⋆ 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 $(pp \to \Lambda^{\uparrow} X)$ Dharmartna & Goldstein PRD 1990

- Need strange quark to polarize a Λ

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



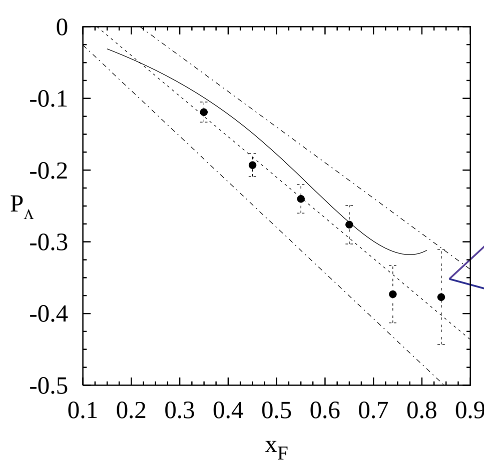
Phases in *hard part* $\hat{\sigma}$
interference of loops and tree level

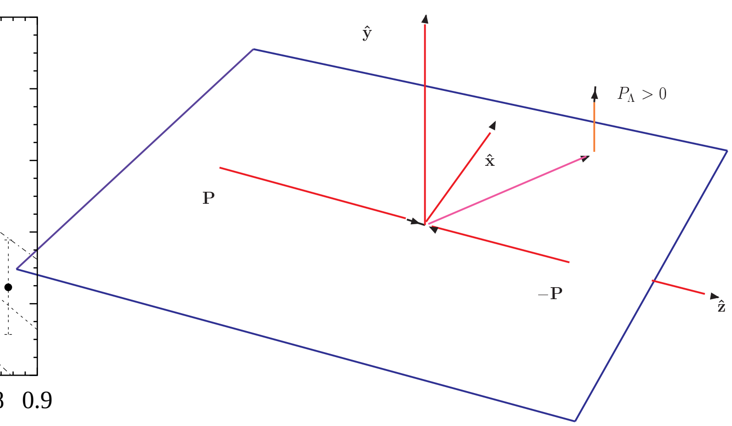
- Polarization $P_\Lambda \sim \frac{m_s \alpha_s}{P_T}$–twist 3 & small $\approx 5\%$ as predicted

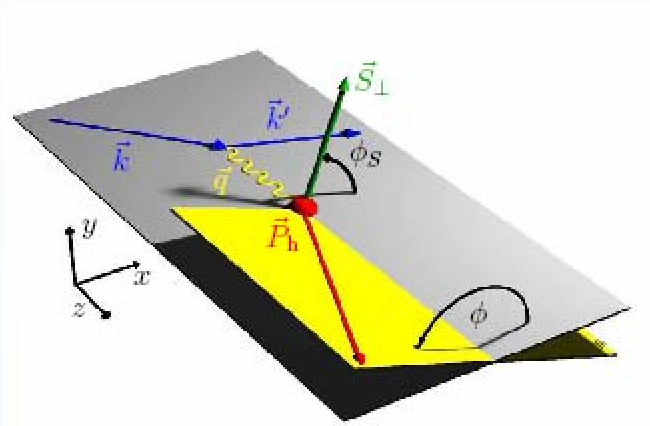
- Experiment *glaringly at odd with this result*

  P_Λ in $p-p$ scattering-Fermi Lab

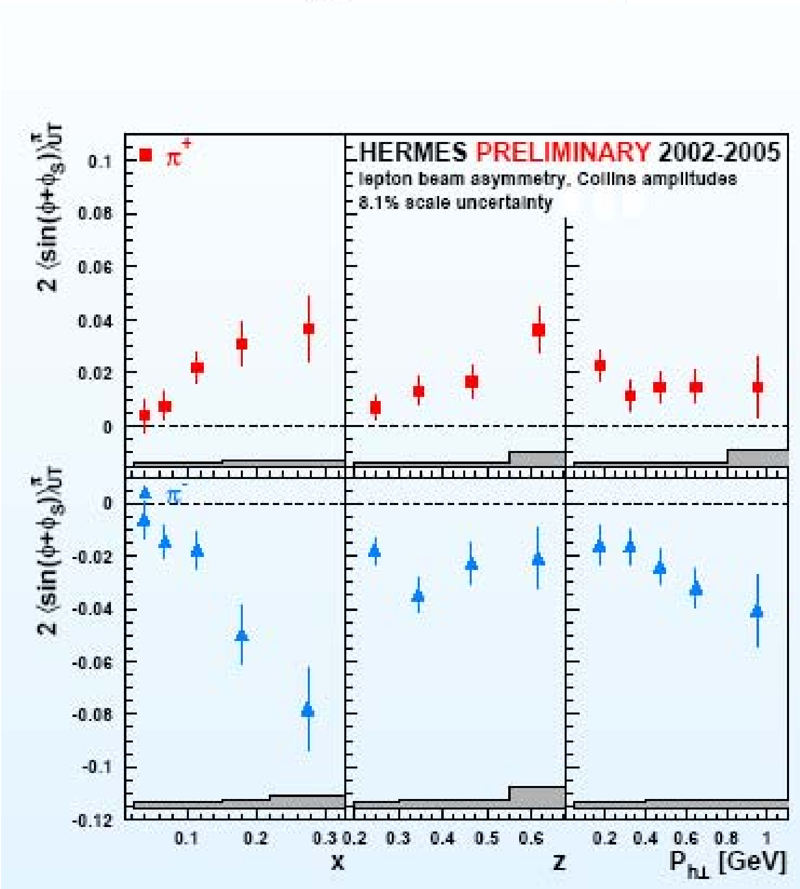
  Heller,...,Bunce PRL:1983

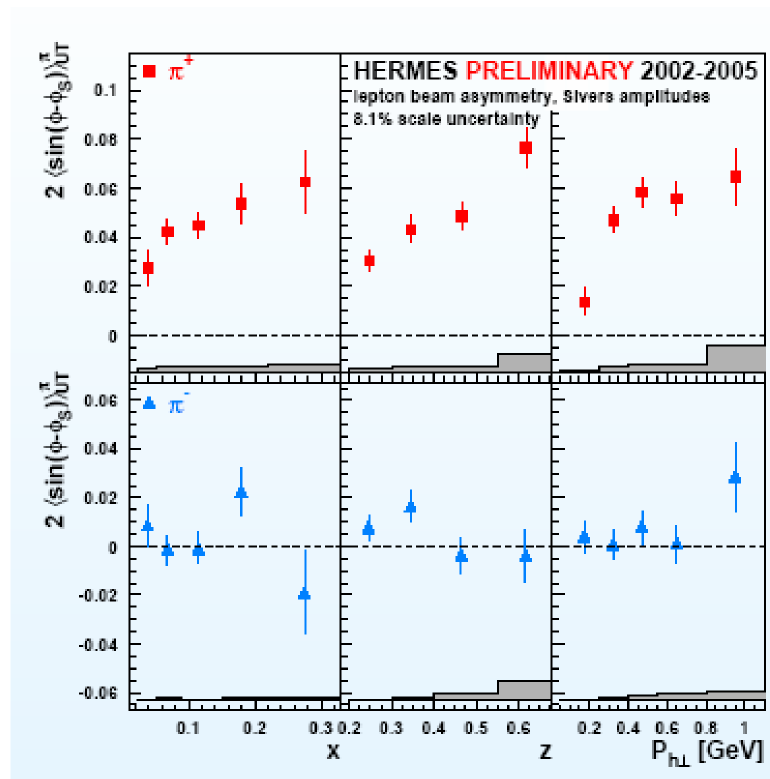




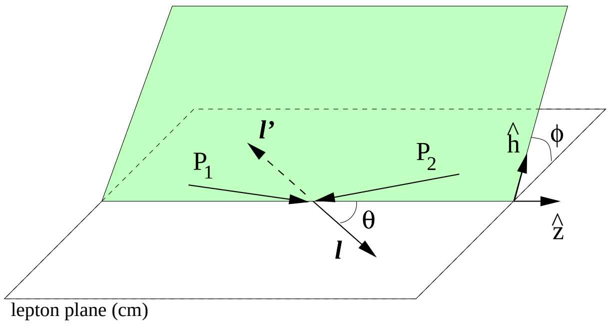


HERMES $ep^{\uparrow} \Rightarrow \pi\ X$





Azimuthal Asymmetry–Unpolarized DRELL YAN



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

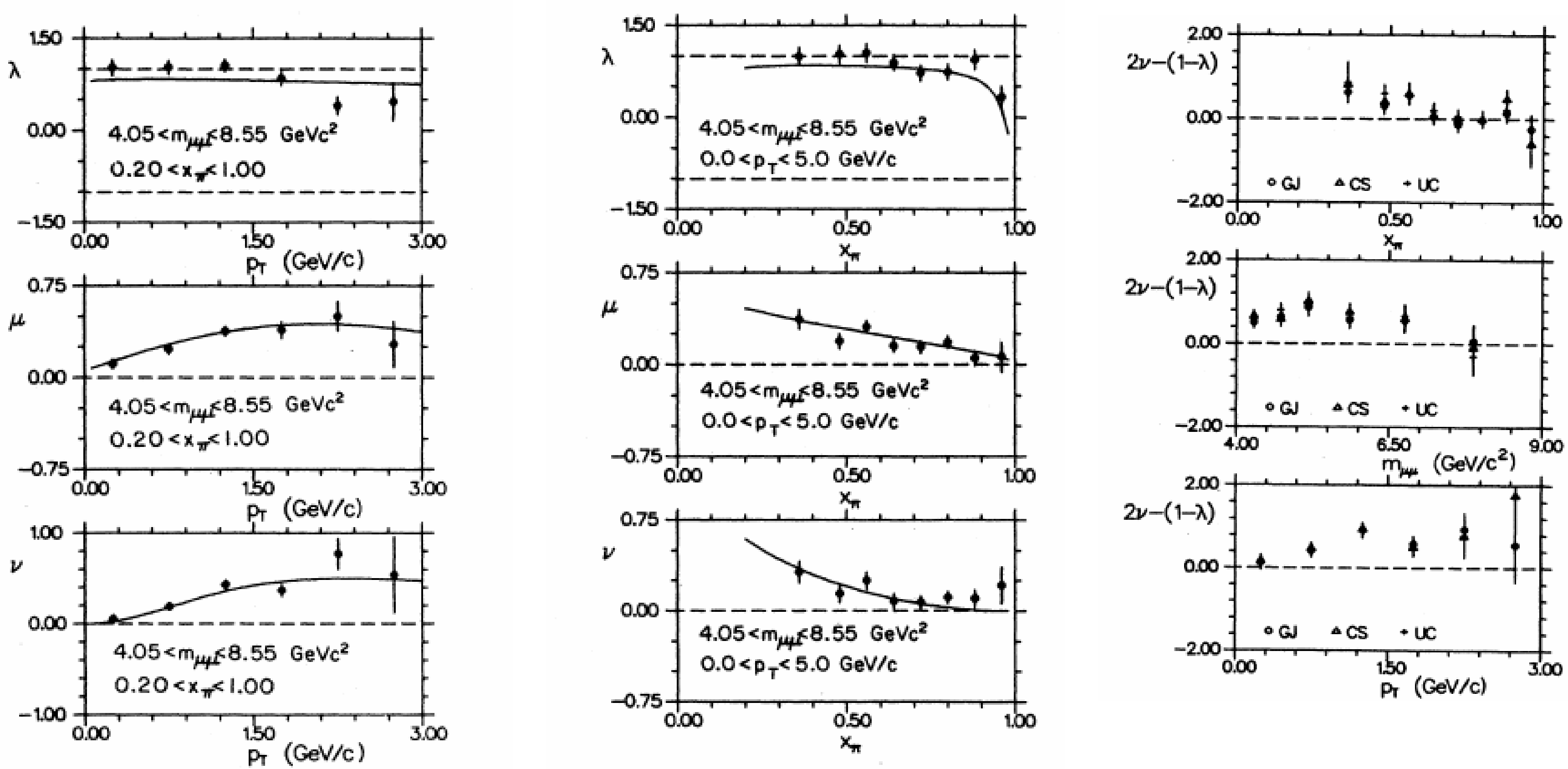
QCD-Parton Model doesn't account for large "AA"

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

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

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

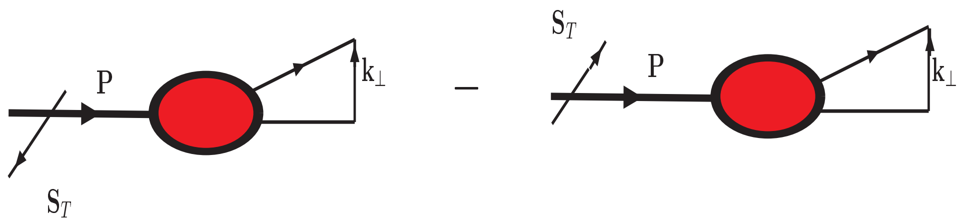
- *Unexpected large* $\cos 2\phi$ – $\nu \sim 10-30\%$ AA



Lam-Tung Relationship Violated

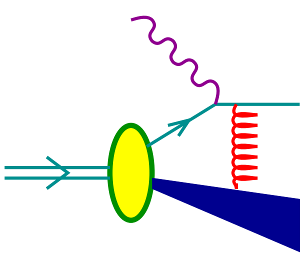
$p_T \sim k_\perp$ TSSAs thru "T-Odd" TMD

- Sivers PRD: 1990, TSSA associated with "T-odd" correlation *transverse* spin and momenta

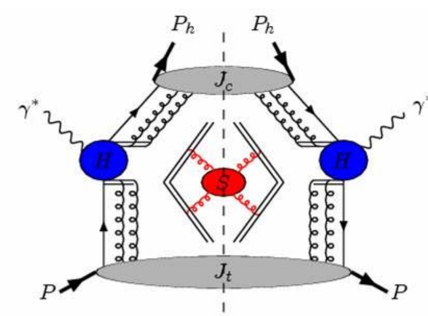


$$\Delta\sigma \sim D \otimes f \otimes \Delta f^{\perp} \otimes \hat{\sigma}_{Born} \quad i\boldsymbol{S}_T \cdot (\boldsymbol{P} \times \boldsymbol{p}_\perp) \to f_{1T}^{\perp}(x, \boldsymbol{p}_\perp)$$

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

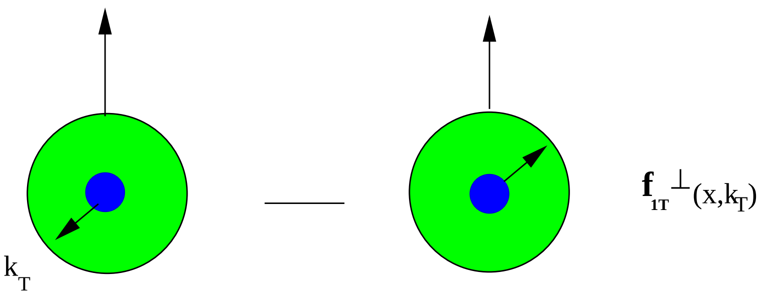
Collins, Metz: PRL 2005 *Universality & Factorization "Maximally" Correlated*

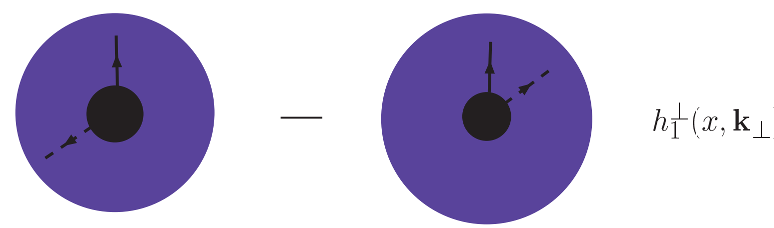
Transversity w/o Target Polarization

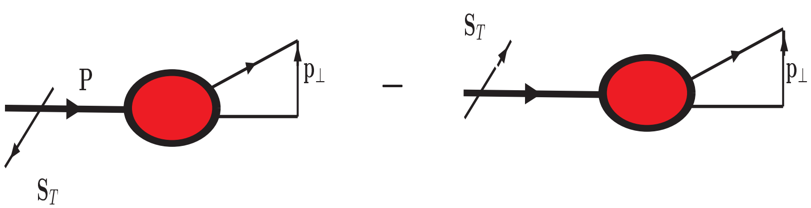
Transversely polarized quark in unpolarized Target Boer,Mulders PRD: 1998

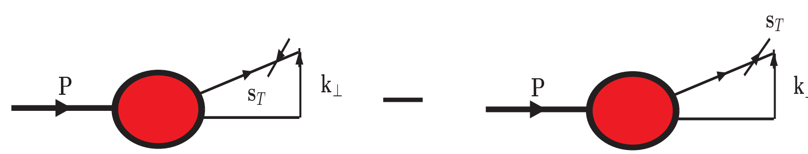
Correlation of transversely polarized *quark spin* with intrinsic $\boldsymbol{k}_\perp$

$$i s_T \cdot (\boldsymbol{p}_\perp \times \boldsymbol{P}) \to h_1^\perp(x, \boldsymbol{k}_\perp)$$









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

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

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

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

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

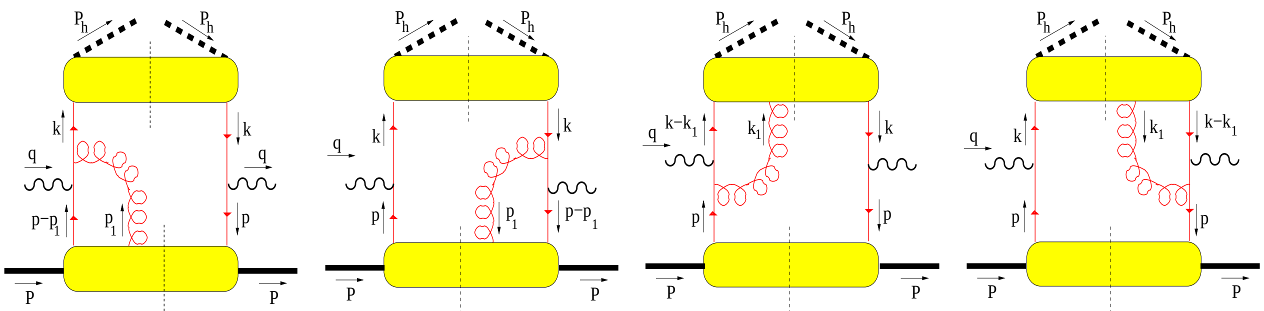
<u>SIDIS cross section</u>

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

T-Odd Effects Incorp. thru Color Gauge Invariant Factorized QCD via 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



etc . . .

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

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

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

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

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

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

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

- The INPUT
  - ⋆ Boer Mulders, Mulders
  - ⋆ Collins Function

- Theoretical Issues
  - ⋆ Sign of Boer Mulders and Mulders function
  - ⋆ Universality of Collins Function

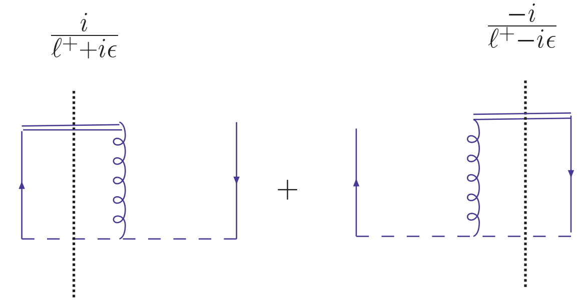
Mechanisms explored thru T-odd Contribution in SIDIS:

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

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

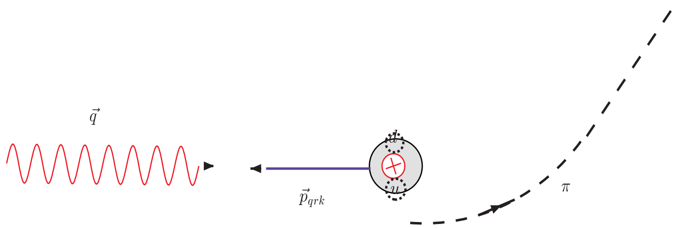
with

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

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 $\delta q^X(x, \mathbf{b}_\perp) = -\frac{1}{2M}\frac{\partial}{\partial\, b_y}(2\tilde{\mathcal{H}}_T(x, \mathbf{b}_\perp) + \mathcal{E}_T(x, \mathbf{b}_\perp))$

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

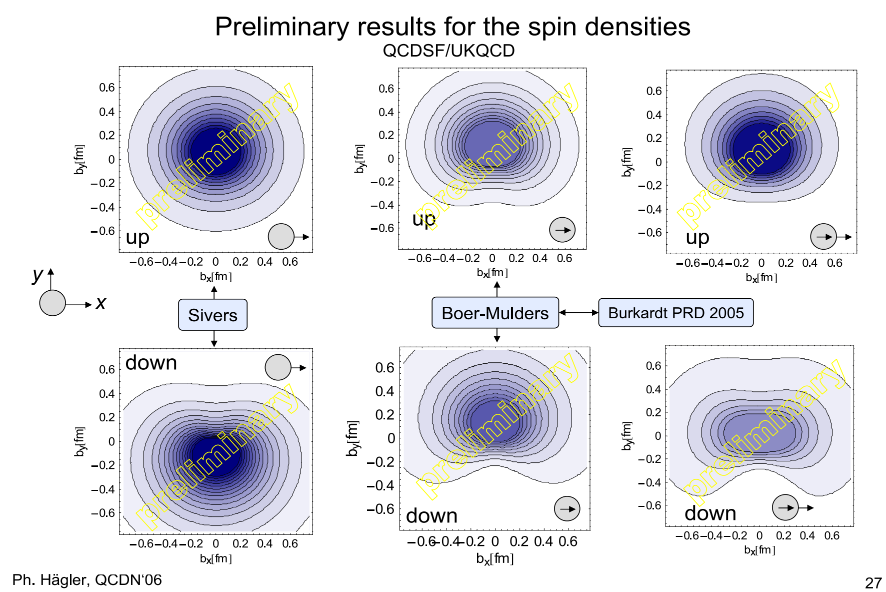
- *Transverse distortion* in impact parameter space of transversly polarized quarks in an unpolarized nucleon Burkardt PRD 2005, Diehl, Hägler EPJC 2005

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

- Supports
  - ⋆ 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

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

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



see talks of Hägler's and Metz

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

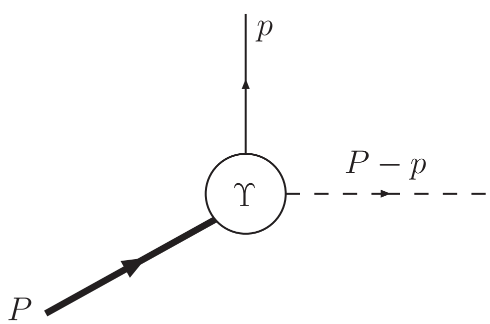
Correlator (account for composite diquark thru anomalous mag moment κ in vertex)

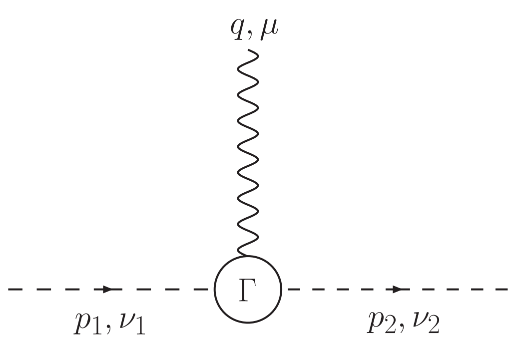
$$\Phi_{ij}(p;P,S) \quad = \quad \sum_\lambda \frac{1}{(2\pi)^3}\,\delta((P-p)^2-m_s^2)\Theta(P^0-p^0)$$

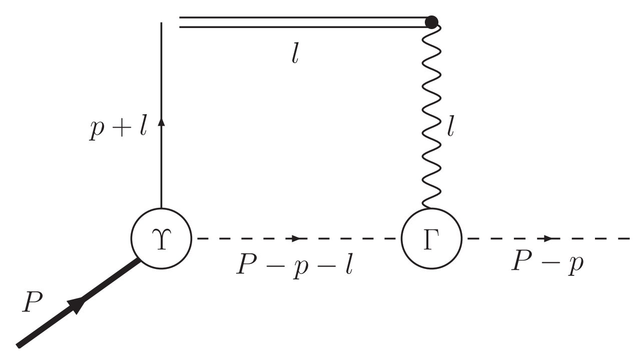
$$\langle P,S|\,\bar\psi_j(0)\,\mathcal{W}[0\,|\,\infty,0,\vec{0}_T]\,|\,dq;\;P-p,\lambda\rangle\langle\,dq;\;P-p,\lambda|\,\mathcal{W}[\infty,0,\vec{0}_T\,|\,0]\,\psi_i(0)\,|P,S\rangle.$$

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

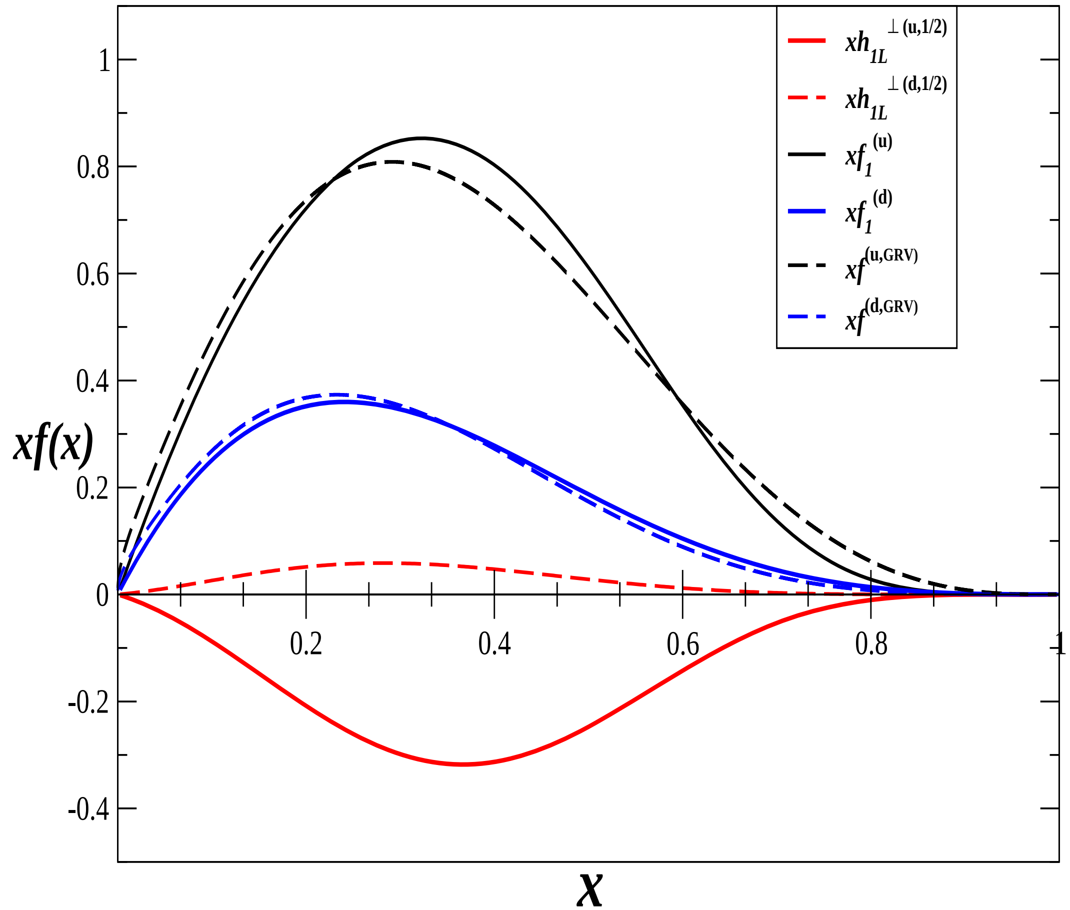
$$\Gamma^{\mu\nu_1\nu_2}_{ax} = -ie_{dq}\left[g^{\nu_1\nu_2}(p_1+p_2)^\mu + (1+\kappa)\left(g^{\mu\nu_2}(p_2+q)^{\nu_1} + g^{\mu\nu_1}(p_1-q)^{\nu_2}\right)\right]$$







Mulders-Kotzinian-$h_{1L}^{\perp}$

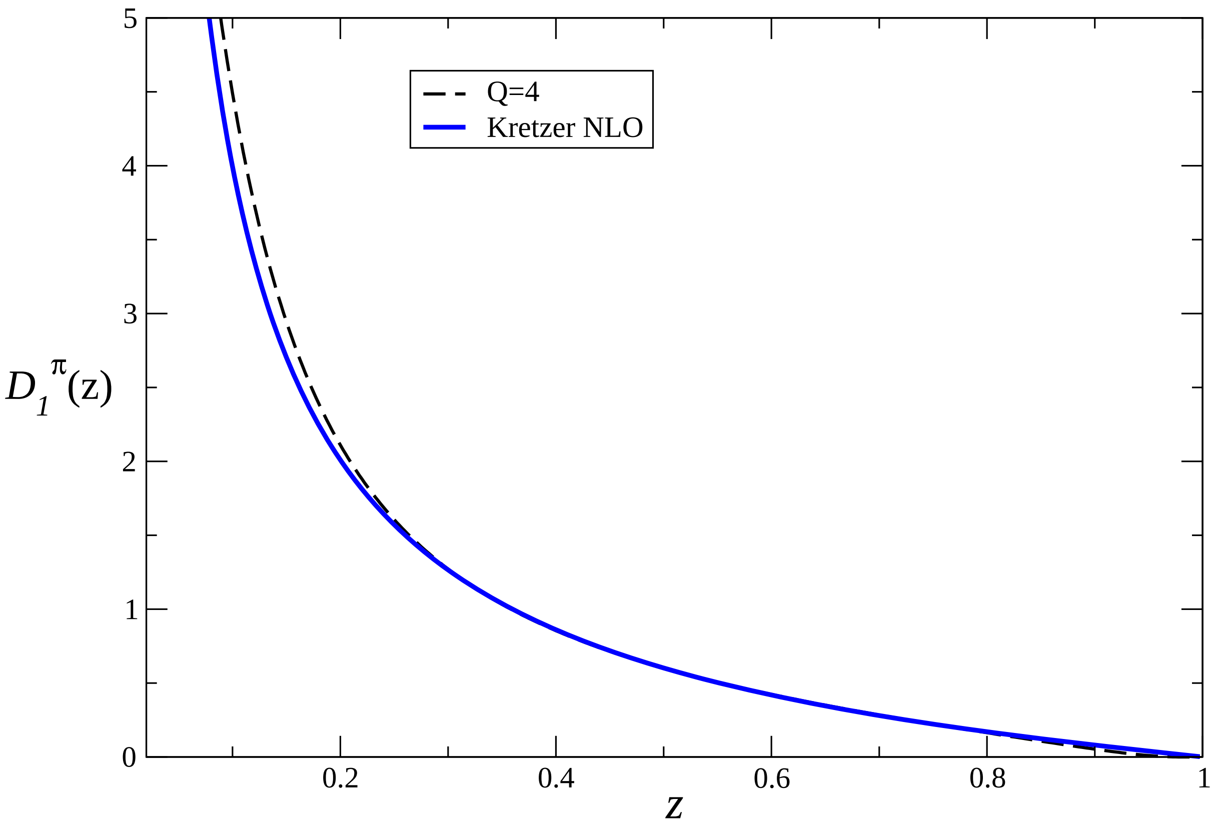


- ⋆ Valence Normalization, $\int_0^1 u(x) = 2$, $\int_0^1 d(x) = 1$
- Black curve- $xu(x)$
- Dashed curve - $xu(x)$ GRV
- Red/Blue curve $xh_1^{\perp(1/2)(u,d)}$

Pion Fragmentation Function

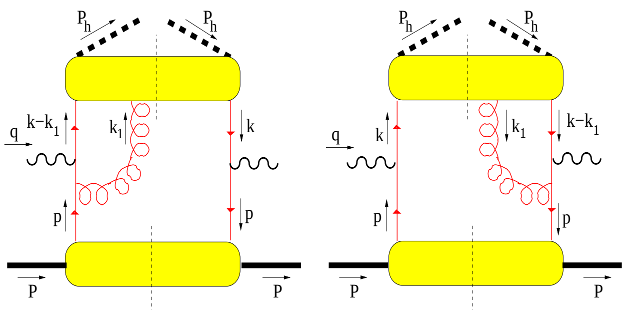
Bacchetta, L.G., Goldstein, Mukherjee in prep

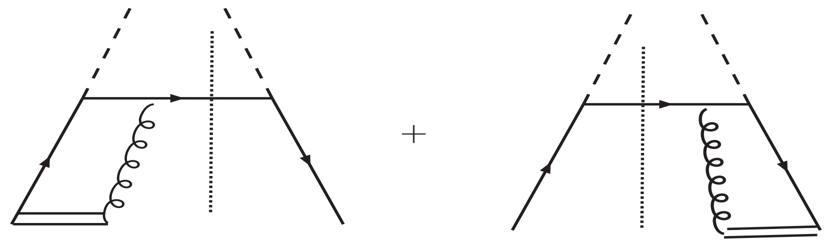
Normalized to Kretzer, PRD: 2000



Gauge Link Contribution to T-Odd Collins Function

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





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

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 prove 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

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

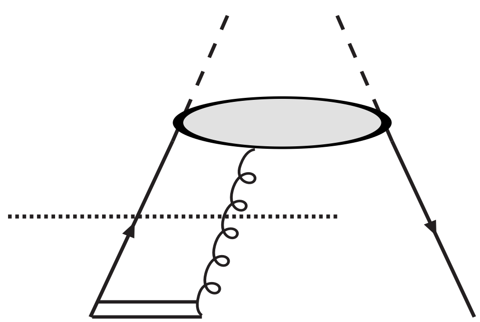
$n = (n^-, n^+, 0)$ (see CS NPB 1982, LG, Hwang, Metz, Schlegel PBL:2006)

- ⋆ t-channel cut vanishes
  - On Eikonal and Spectator
- ⋆ s-channel cut
  - On Fragmenting quark and gluon contributes

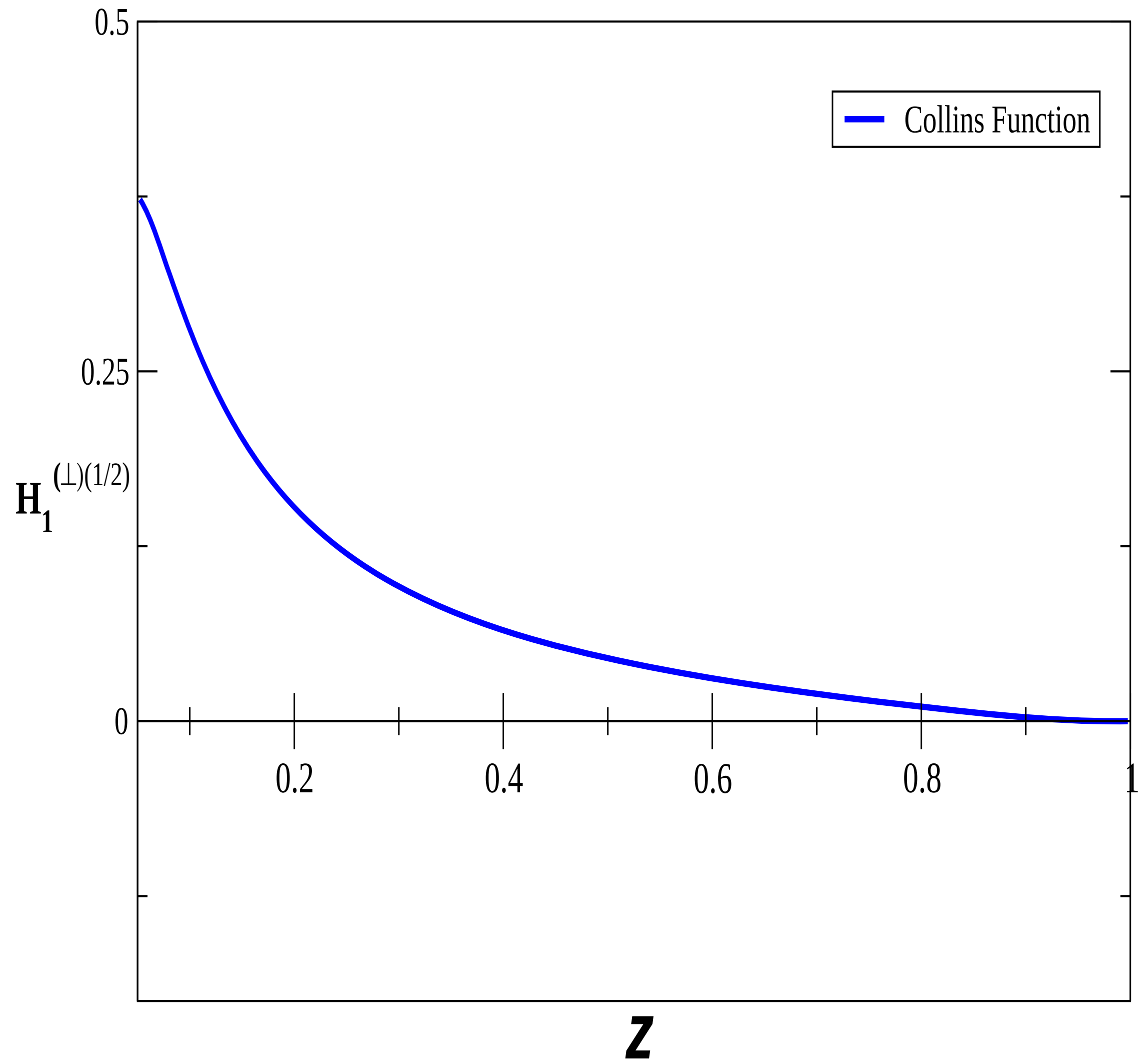
Reciprocity Fails, "T-odd" Fragemtation Function Universal between e^+e^- and SIDIS

Bacchetta, L.G., Goldstein, Mukherjee

Re-analysis and Kaons

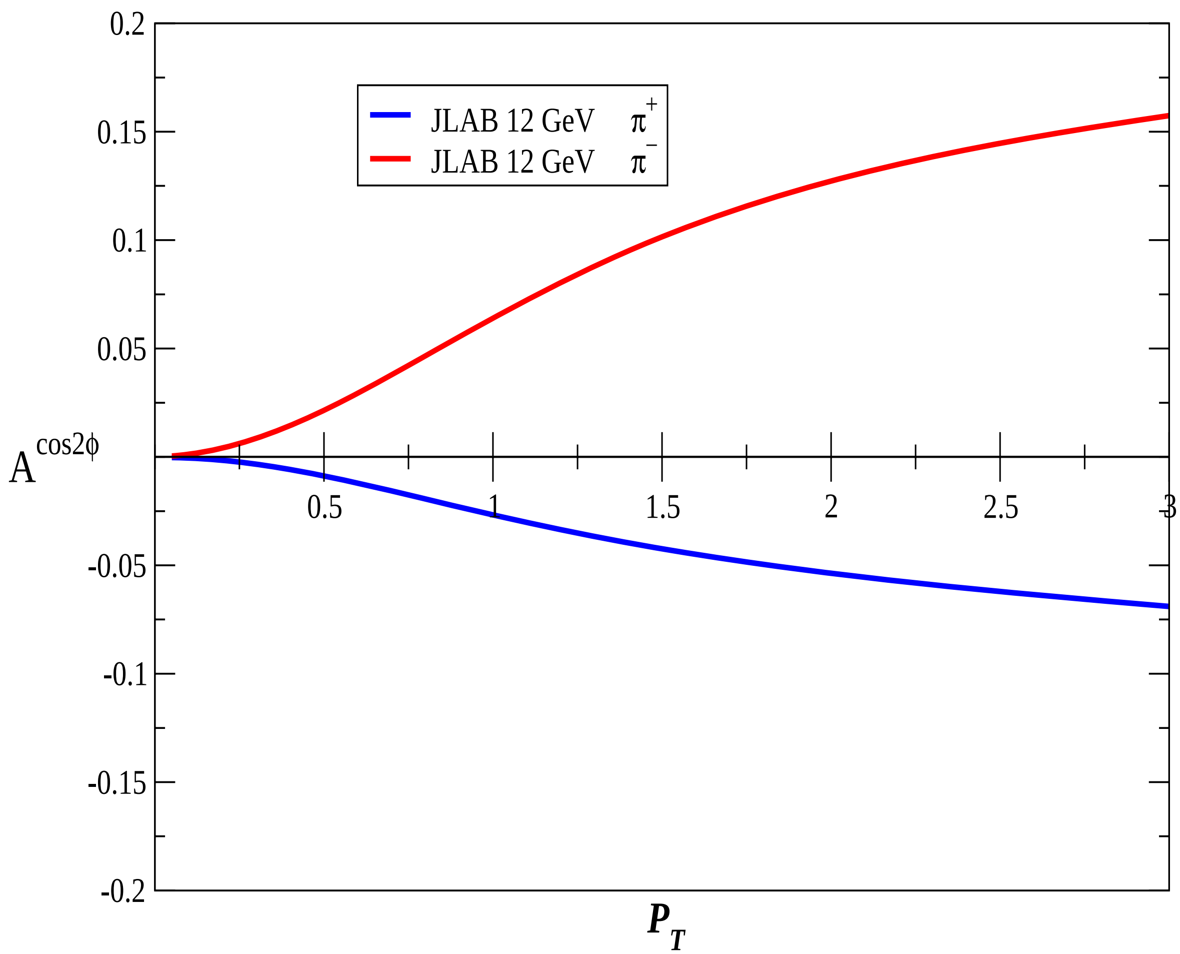


$$\frac{-i}{\ell^{-} - i\epsilon}$$

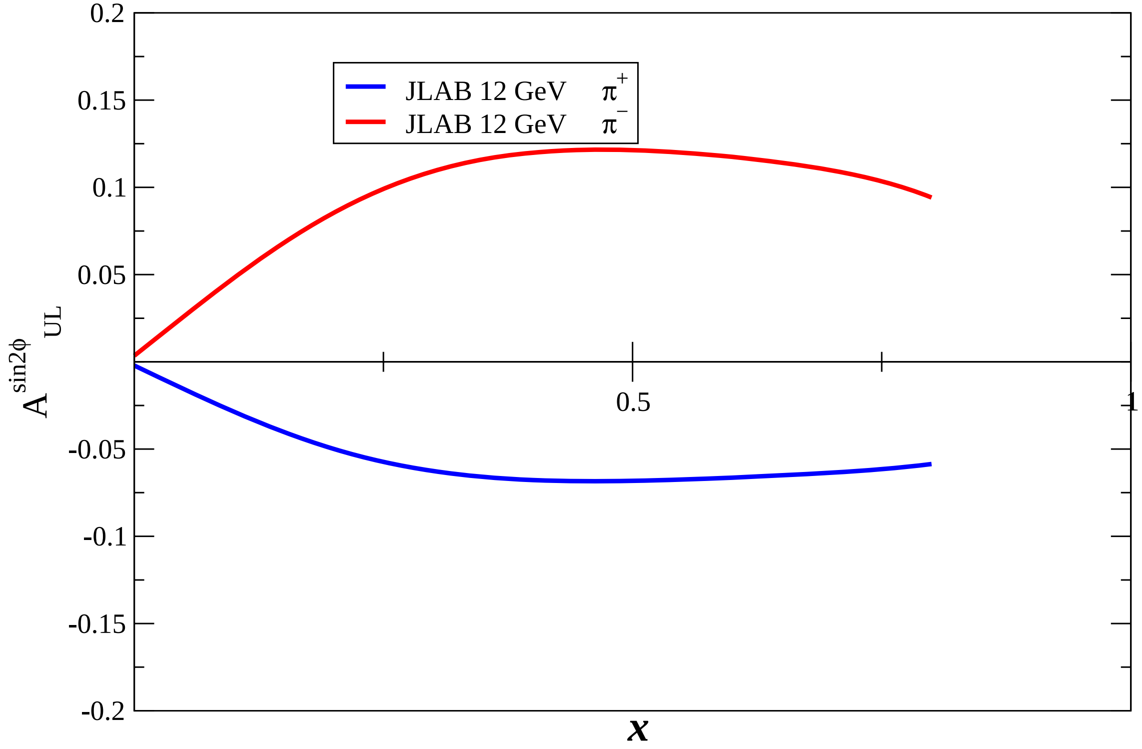


CLAS12 PAC 30-Avakian, Meziani. . . L.G. . .

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

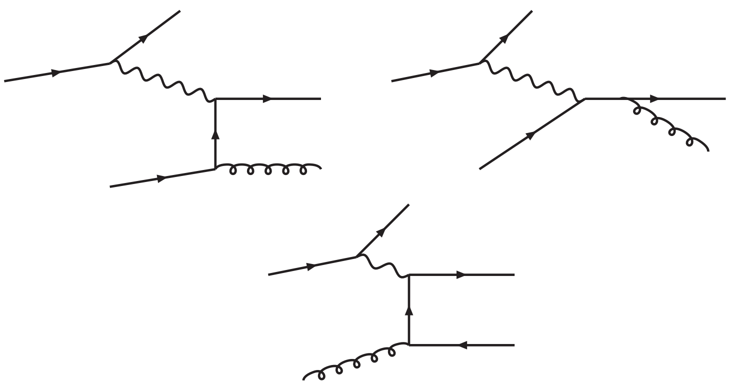


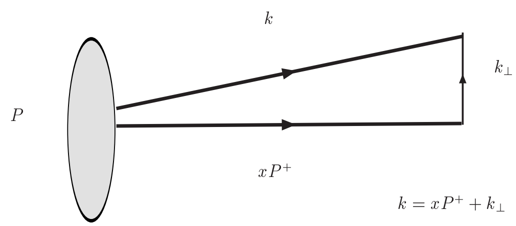
$$A_{UL} = \frac{2(1-y)}{1+(1-y)^2} \frac{h_{1L}^{\perp(1)} H_1^{\perp(1)}}{f_1 D_1}$$



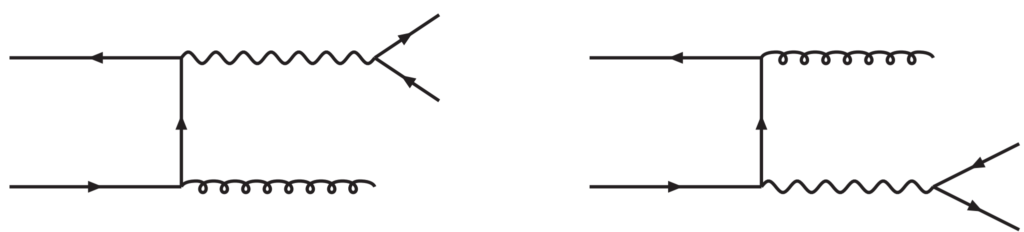
$\cos 2\phi$ JLAB, EIC, GSI, JPARC ...

- Georgi and Mendez 1975, Kroll and König 1982 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 $h_1^\perp \otimes \bar{h}_1^\perp$



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