Single-Spin Asymmetries

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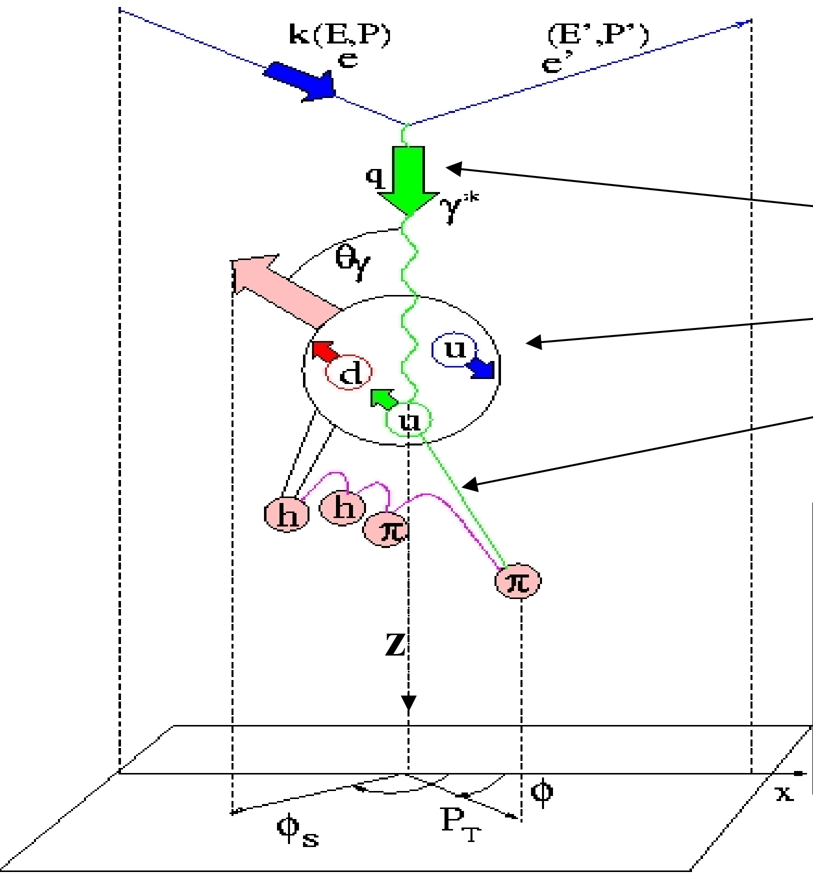
Hall-C Summer Workshop, August 25 JLab

Physics motivation
k_T-effects and Collins asymmetry
TMD studies from unpolarized target data
TMD studies from polarized target data
Summary

Physics Motivation

➢ Describe the complex nucleon structure in terms of quark and gluon degrees of freedom using SIDIS



Cross section is a function of scale variables *x,y,z*

$$\nu = E - E'$$
$$y = \nu / E$$
$$x = Q^2 / 2M\nu$$
$$z = E_h / \nu$$

In 1D world (no orbital motion)

- quarks polarized if nucleon is polarized→f_1,g_1,h_1
- No azimuthal asymmetries in LO

Transverse spin effects are observable as correlations of transverse spin and transverse momentum of quarks.

SIDIS ($\gamma^* p \to \pi X$) x-section at leading twist:

$$\frac{d\sigma}{dx\,dy\,dz\,d^2\vec{P}_h} = \frac{4\pi\alpha^2 s}{Q^4}[x(1-y+y^2/2)F_{UU}^{(1)}$$

$$-x(1-y)\cos(2\phi)F_{UU}^{(2)}$$

$$\lambda_l\lambda(1-y/2)xF_{LL}$$

$$\lambda(1-y)x\sin(2\phi)F_{UL}$$

$$|S_\perp|(1-y+y^2/2)x\sin(\phi-\phi_S)F_{UT}^{(1)}$$

$$\lambda_l|S_\perp|y(1-y/2)x\cos(\phi-\phi_S)F_{LT}$$

$$|S_\perp|(1-y)x\sin(\phi+\phi_S)F_{UT}^{(2)}$$

$$\frac{1}{2}|S_\perp|(1-y)x\sin(3\phi-\phi_S)F_{UT}^{(3)}]$$

Unpolarized target
Longitudinally pol.
Transversely pol.

TMD PDFs: k_T-even	TMD PDFs: k_T-odd	FFs
f_1		D_1
	$h_1^\perp$	$H_1^\perp$
g_1		D_1
	$h_{1L}^\perp$	$H_1^\perp$
	f_{1T}	D_1
	g_{1T}	D_1
h_1		$H_1^\perp$
	$h_{1T}^\perp$	$H_1^\perp$
$\sim(1-x)^3$	$\sim(1-x)^4$	

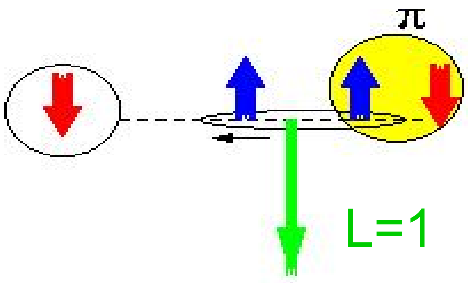
The structure functions depend on Q^2, x_B, z, P_{hT}

Brodsky et al 2006

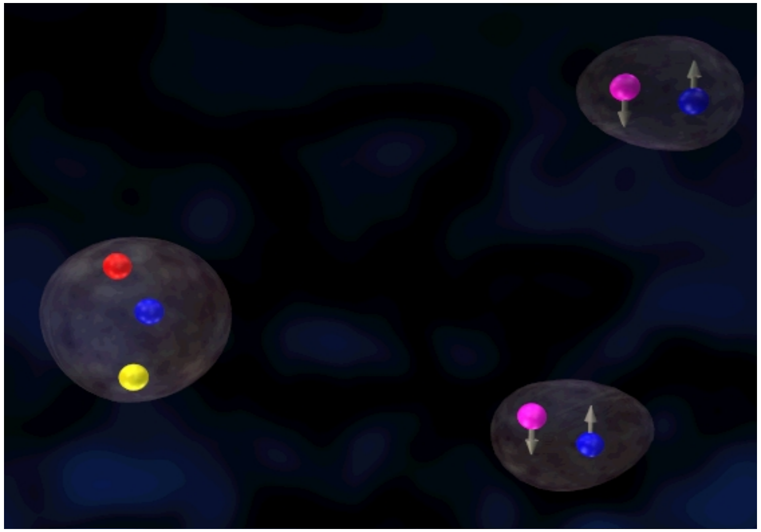
- Factorization of k_T-dependent PDFs proven at low P_T of hadrons (**Ji et al Phys.Lett B 597, 299 (2004)**)

Collins effect

Collins Fragmentation

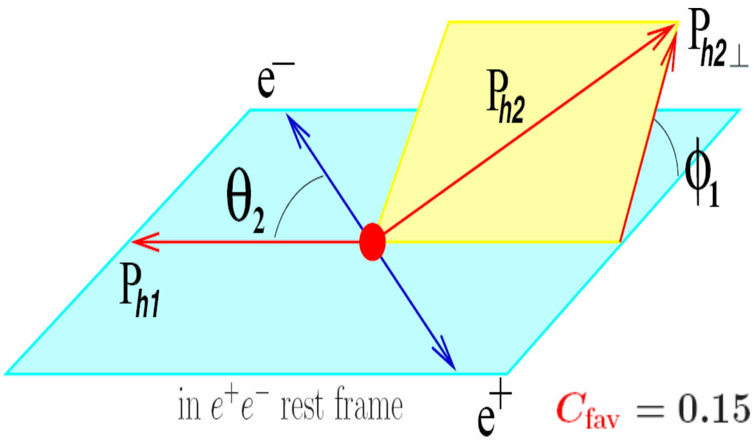


String fragmenation (Artru)



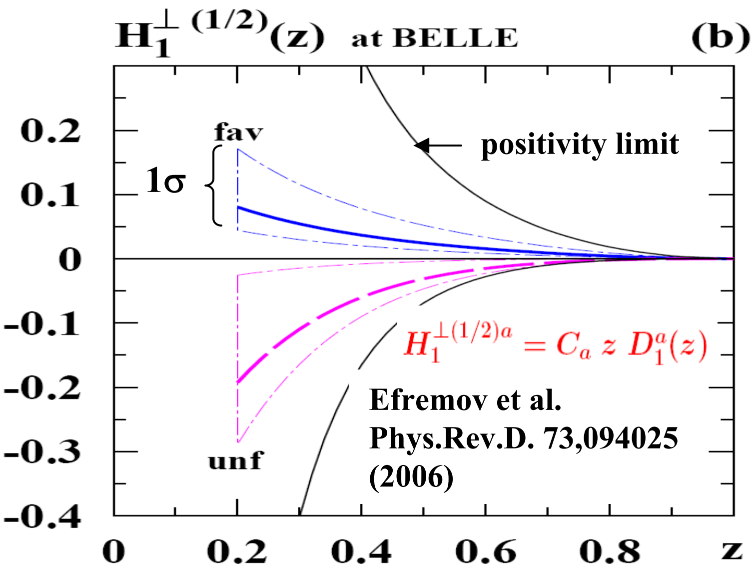
- L/R SSA generated in fragmentation
- Unfavored SSA with opposite sign
- No effect in target fragmenation

BELLE: Asymmetries in $e^+e^- \rightarrow h_1 h_2 X$ ($H^{\perp}_1$ $\bar{H}^{\perp}_1$)

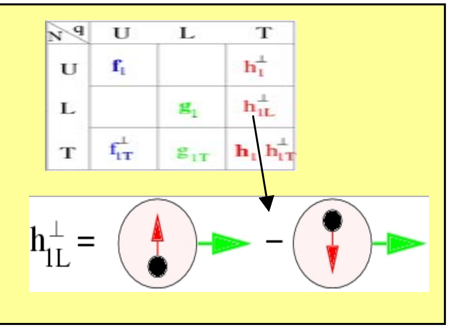


$C_{\rm fav} = 0.15, \quad C_{\rm unf} = -0.45$

sign preferred by HERMES

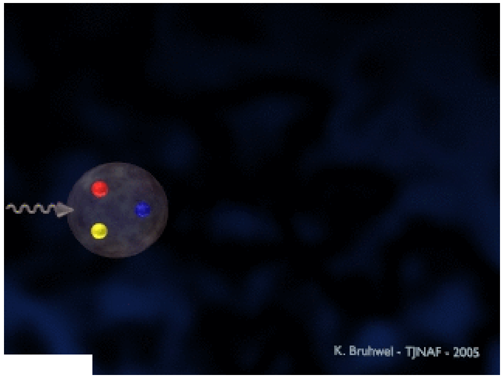


Collins fragmentation & Kotzinian-Mulders Asymmetry

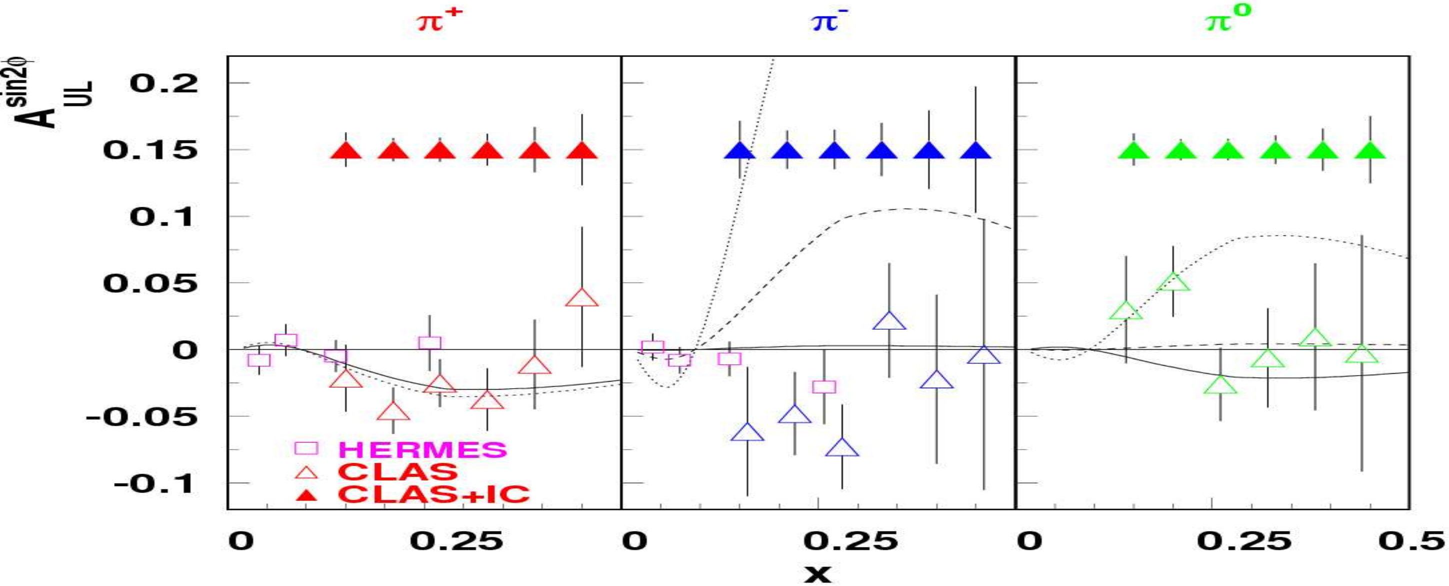


Longitudinally polarized target:

CLAS at 6 GeV



$$\sigma_{UL}^{KM} \sim (1-y) h_{1L}^\perp H_1^\perp$$

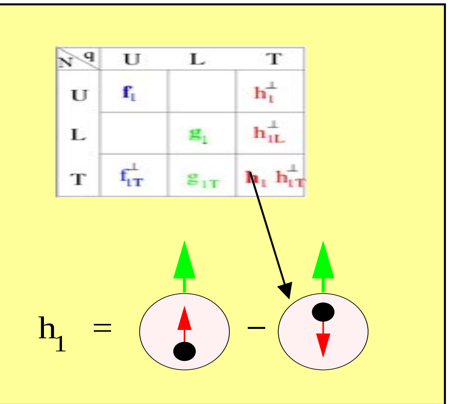


curves, χQSM
from Efremov et al

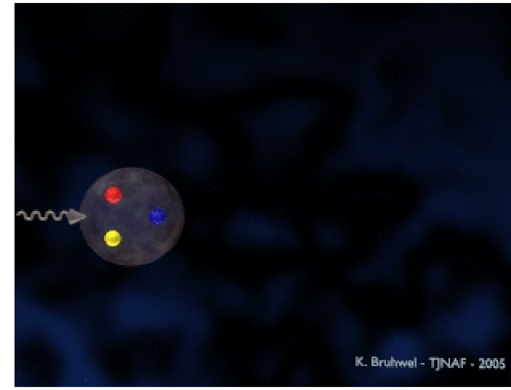
$$H_1^{\perp u \to \pi^+} \approx -H_1^{\perp u \to \pi^-}$$

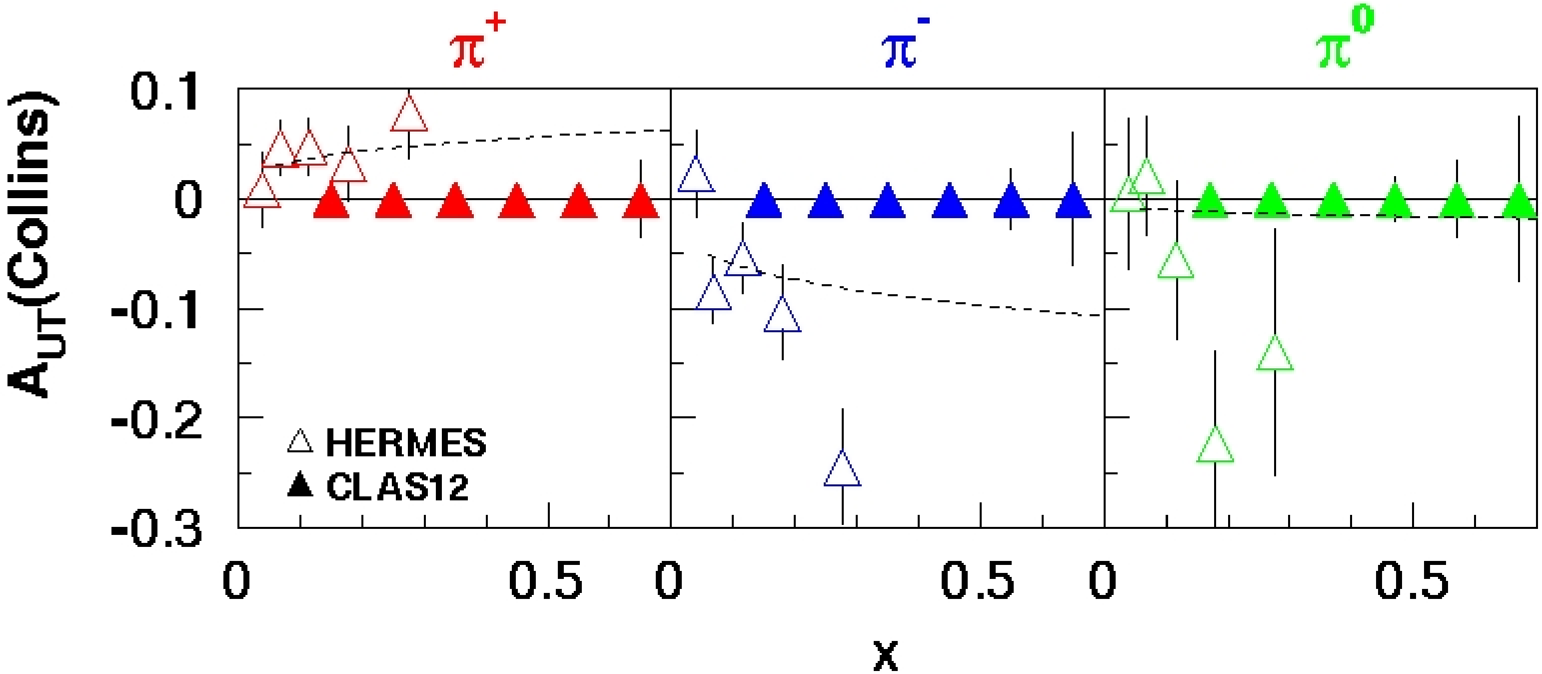
- **Study the Collins asymmetry with longitudinally polarized target (approved for 60 days) will provide independent information on the Collins function.**
- **Measure the twist-2 Mulders TMD (real part of interference of L=0 and L=1 wave functions)**

Collins Effect



$$\sigma_{UT}^{Collins} \sim (1-y)\, h_1 H_1^{\perp}$$

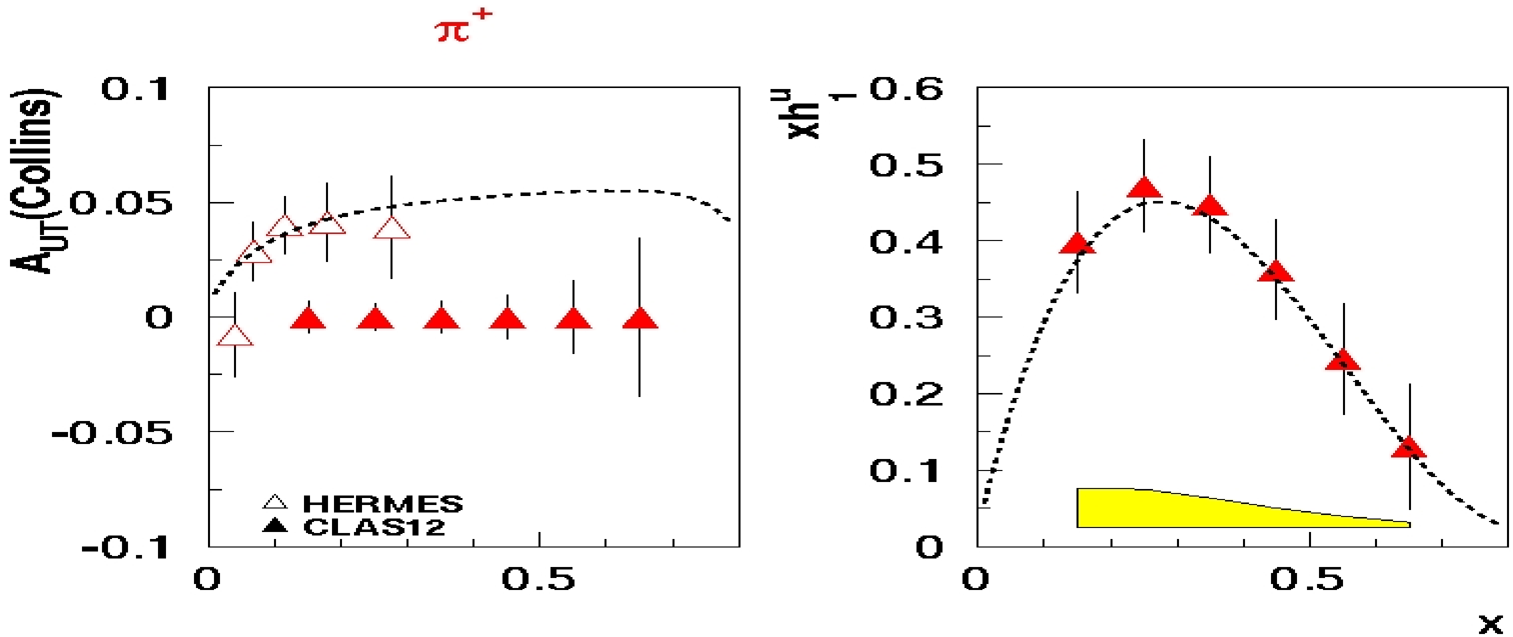




Study the Collins asymmetry for all 3 pions with a **transversely polarized target** will provide independent information on the Collins function.

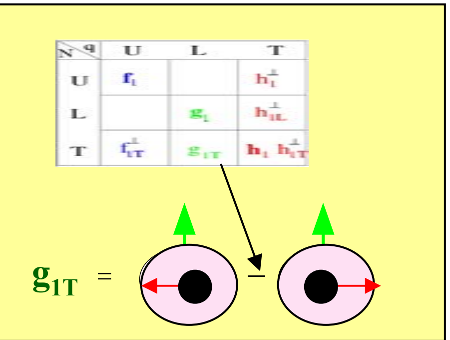
CLAS12: Transversity projections

$$A_{UT}^{Collins} \sim (1-y)\, h_1 H_1^{\perp}$$



Simultaneous measurement of, exclusive $\rho, \rho+, \omega$ with a transversely polarized target

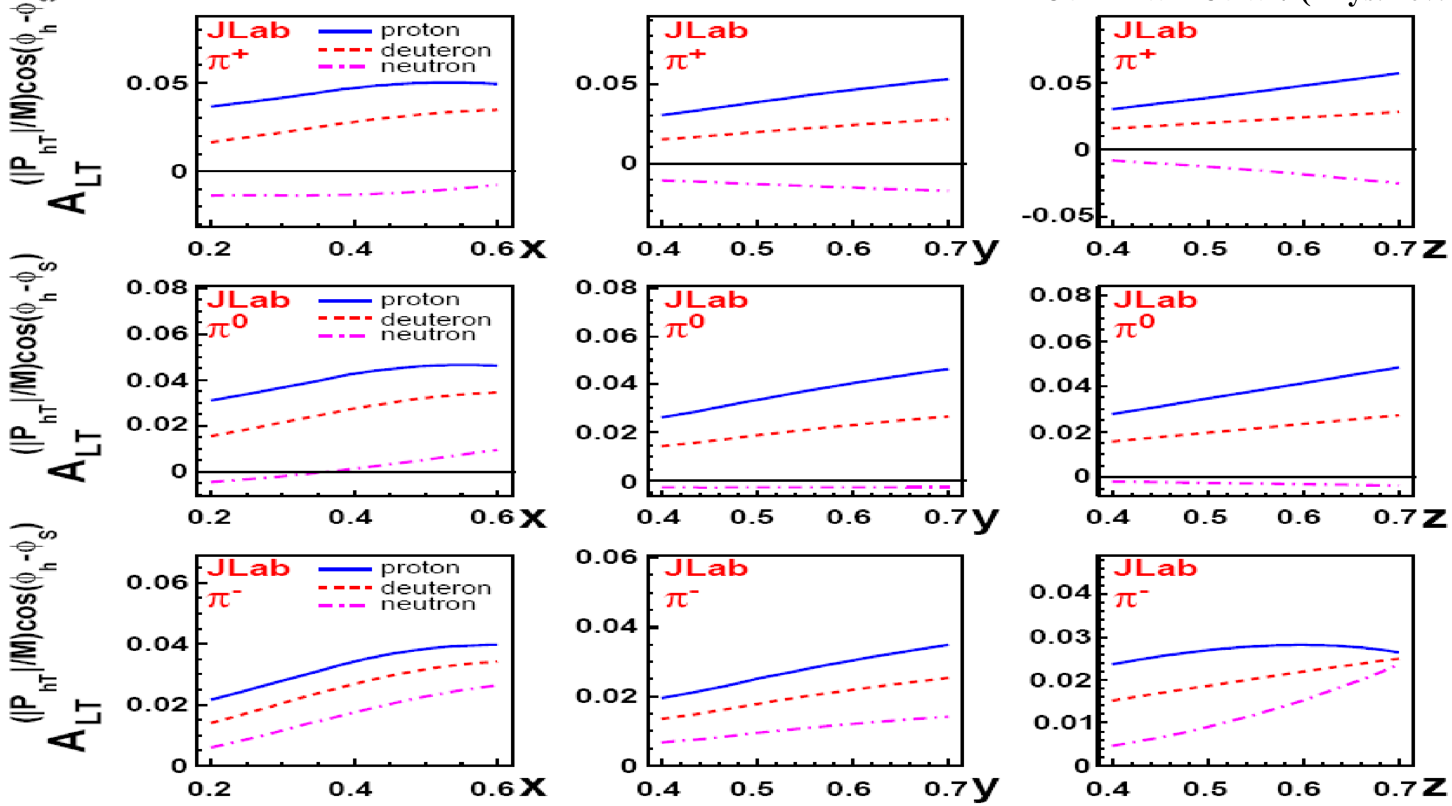
Collins function required to extract transversity from transverse target SSA measurements



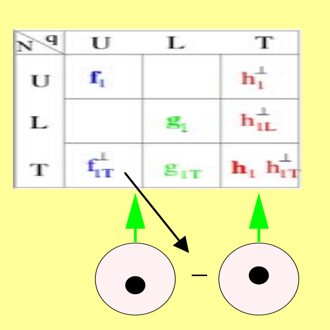
Longitudinally polarized quarks in the transverse target

$$\sigma_{LT}^{\cos\phi} \propto \lambda_e S_T y(1-y/2)\cos(\phi-\phi_S)\sum_{q,\bar{q}} e_q^2 x g_{1T}^q(x) D_1^q(z)$$

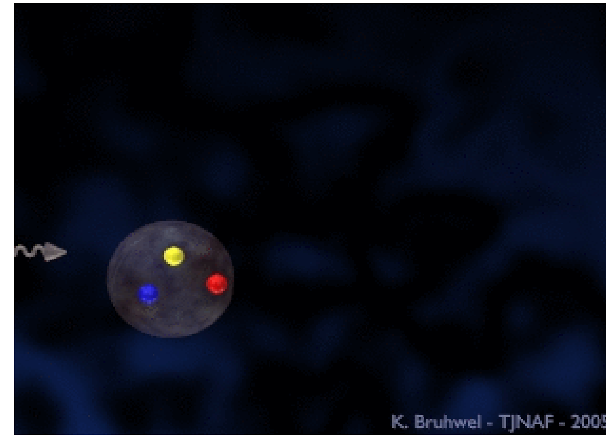
Kotzinian et al. **(Phys.Rev. D73,114017 (2006)**



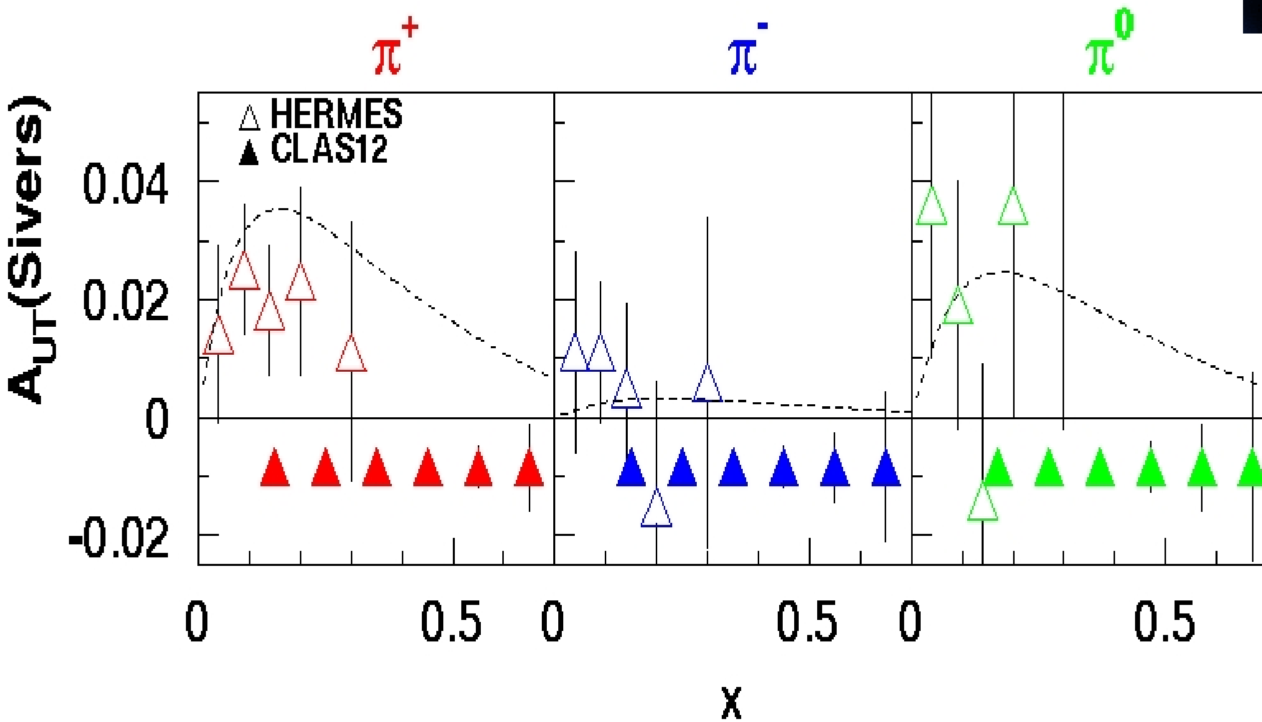
Superior beam polarization at JLAB makes feasible A_{LT} measurement (comes for free with transverse target)



Sivers effect



$$\sigma_{UT}^{Sivers} \sim (2-2y+y^2) f_{1T}^{\perp} D_1$$



- L/R SSA generated in distribution
- Hadrons from struck quark have the same sign SSA
- Opposite effect in target fragmentation

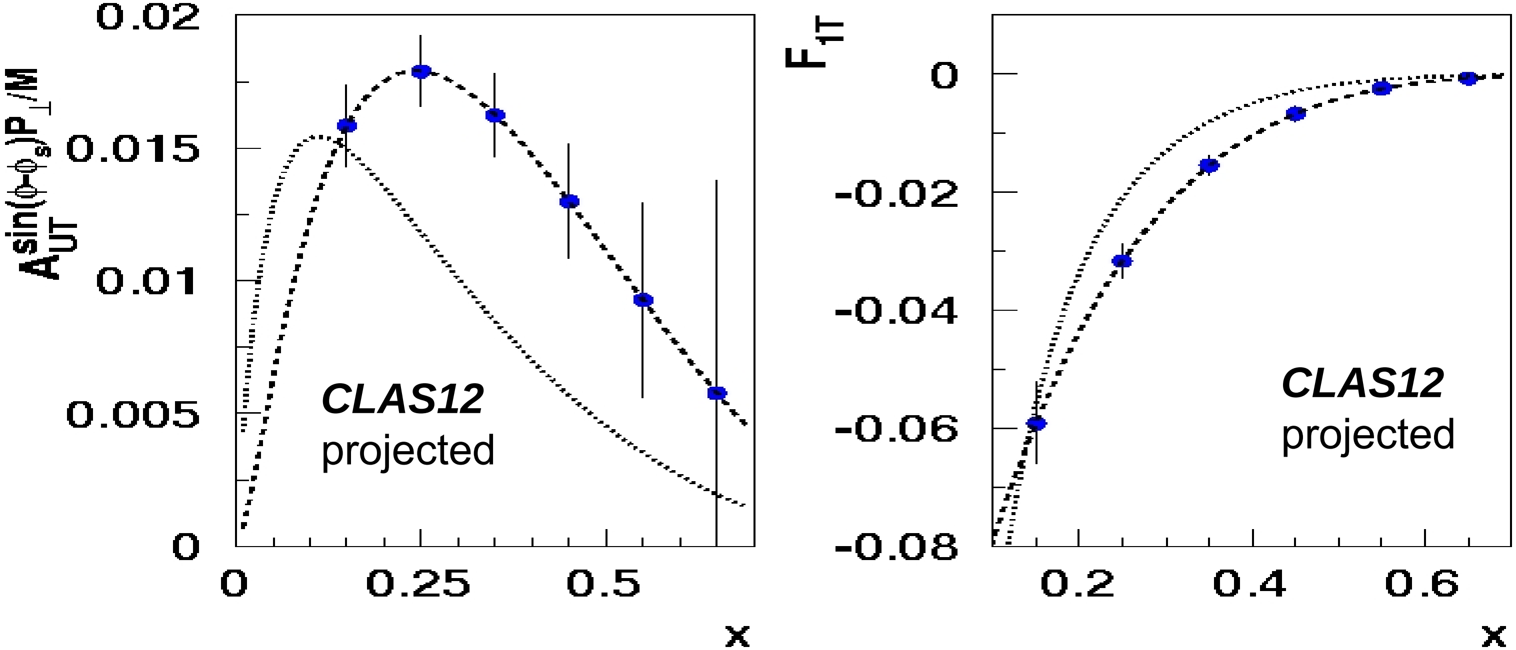
Requires: non-trivial phase from the FSI + interference between different helicity states

CLAS12: Sivers effect projections

In large Nc limit:
$f_{1T}^{u} = -f_{1T}^{d}$

$F_{1T}=\sum_q e_q^2 f_{1T}^{\perp q}$

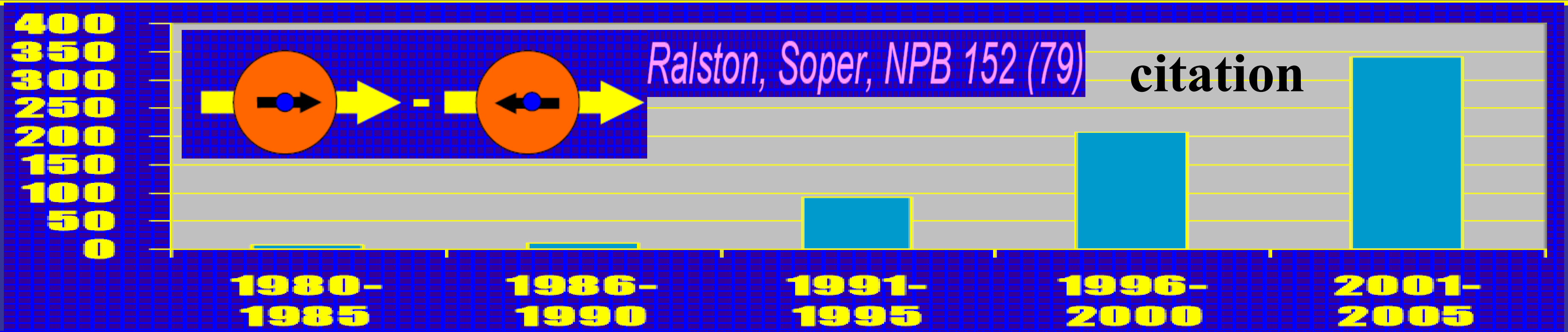
Efremov et al
(large x_B behavior of
f_{1T} from GPD E)

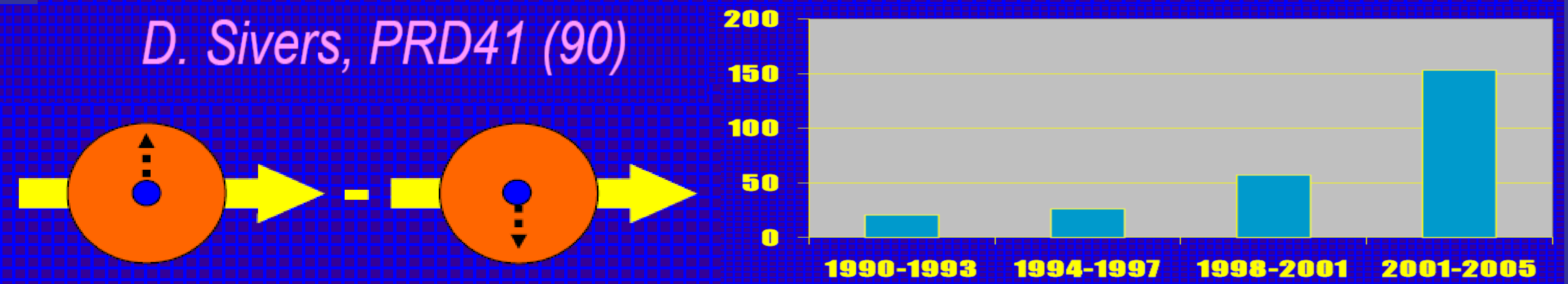


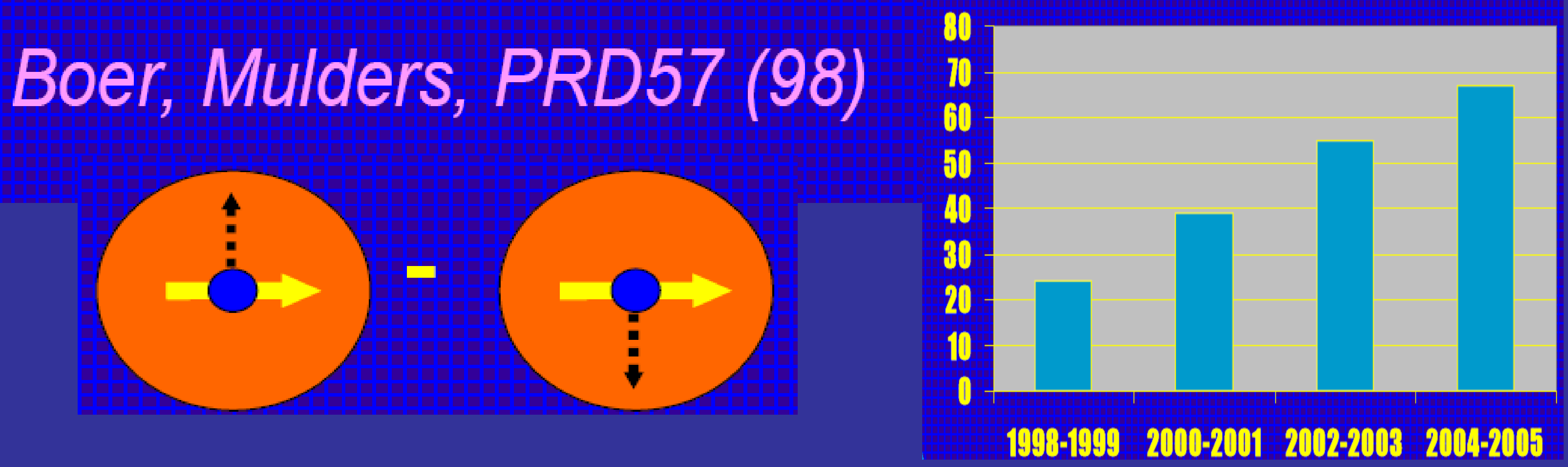
Sivers function extraction from A_{UT} (π^0) does not require information on fragmentation function. It is free of HT and diffractive contributions.

A_{UT} (π^0) on proton and neutron will allow flavor decomposition w/o info on FF.

Birth and growth of transversity distributions

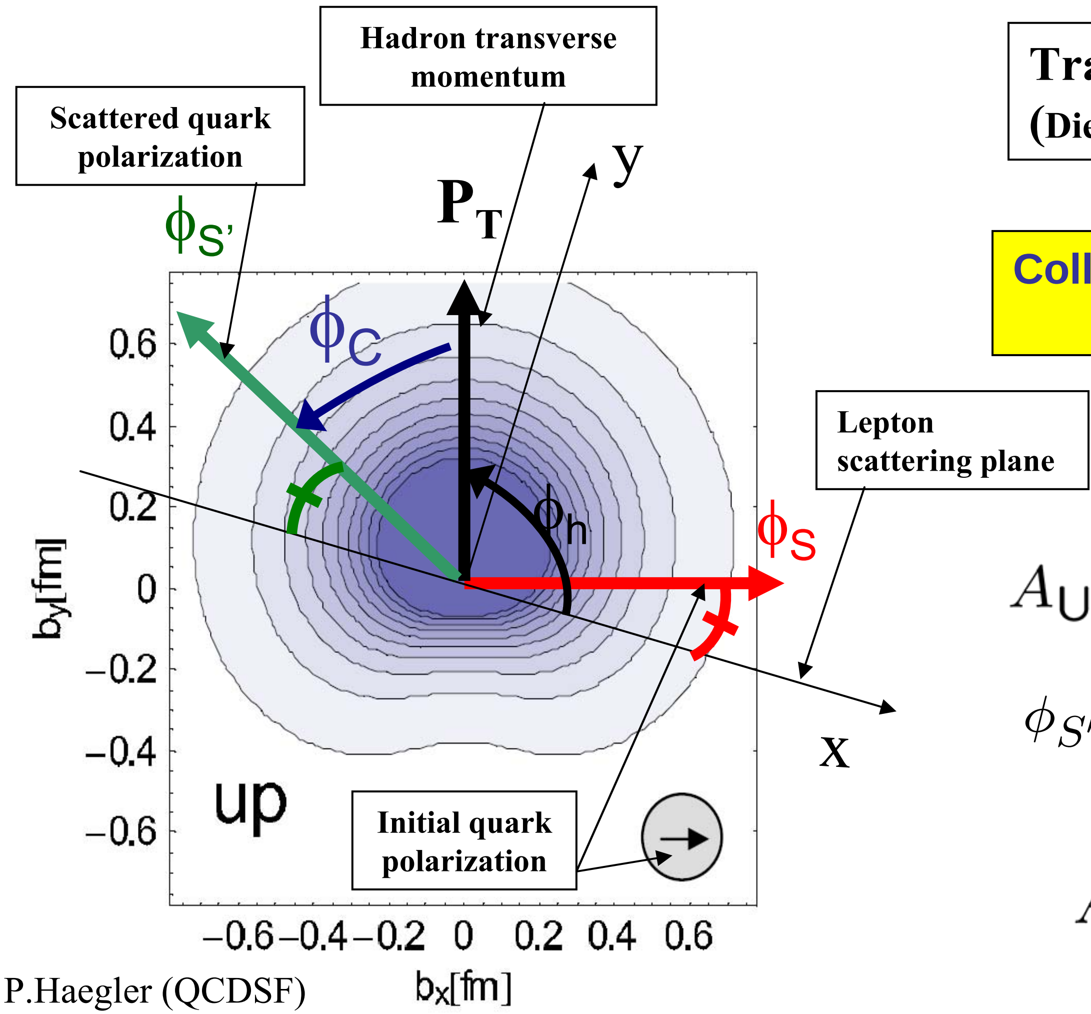






A.Bacchetta (Frascati-2006)

Boer-Mulders effect



P.Haegler (QCDSF)

Transverse position shift → P_T (Diehl GPD2006)

Collins Effect: azimuthal modulation of the fragmentation function

Collins angle: ϕ_C

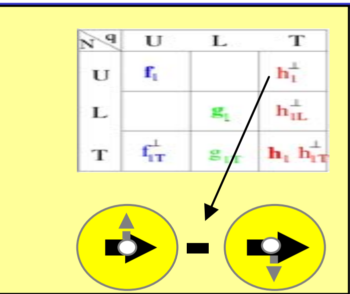
$$A_{UU} \propto h_1^{\perp} H_1^{\perp} \sin(\underbrace{\phi_h - \phi_{S'}}_{\phi_C})$$

$$\phi_{S'} = \pi - \phi_S = \pi - (\phi_h - \pi/2)$$

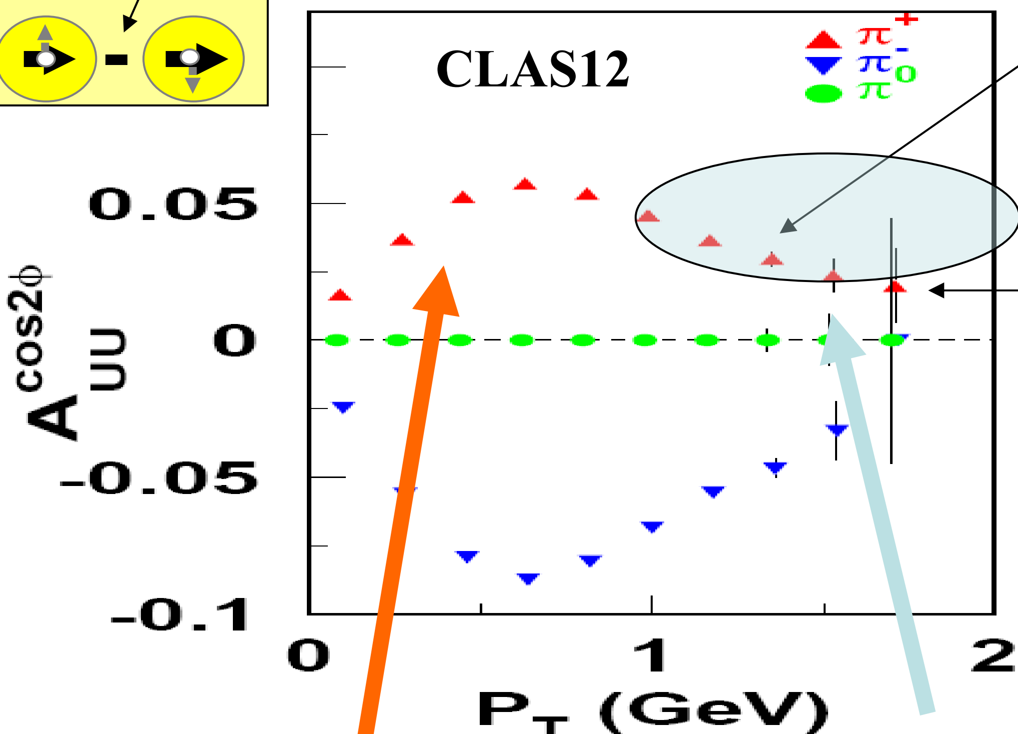
$$A_{UU} \propto h_1^{\perp} H_1^{\perp} \cos(2\phi_h)$$

Sideways shift in distribution of transversely polarized quarks in the unpolarized proton may lead to Collins asymmetry for final state hadrons (**Burkardt,Diehl,Hagler**)

Collins asymmetry & Boer-Mulders Effect



$$A_{UU}^{\cos 2\phi} \propto h_1^{\perp} H_1^{\perp}$$



In the perturbative limit $1/P_T^2$ behavior expected (F.Yuan)

quark-scalar diquark model

$$\frac{h_1^{\perp}}{f_{1T}^{\perp}} = 1$$

$$\frac{H_1^{\perp u\to\pi^+}}{H_1^{\perp u\to\pi^-}} = -1$$

bag model

$$\frac{h_1^{\perp}}{f_{1T}^{\perp}} = \frac{3}{2}$$

$4<Q^2<5$ (2000h @ 11 GeV with 10^{35}sec^{-1}cm^{-2})

$$\Lambda_{QCD} \ll P_T \ll Q$$

Non-perturbative TMD

Perturbative region

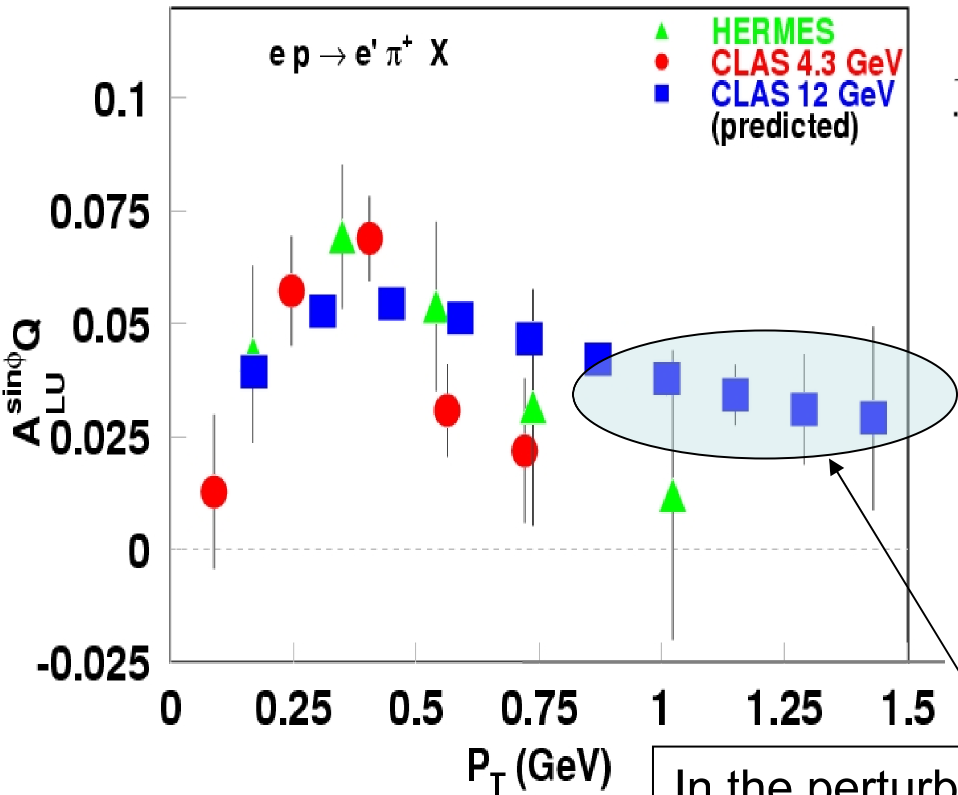
- BM cos2ϕ moment: the only leading twist azimuthal moment for unpolarized target
- **P_T**-dependence of BM asymmetry allows studies of transition from non-perturbative to perturbative description (Unified theory by Ji et al).
- More info will be available from SIDIS (HERMES,COMPASS,ZEUS) and DY (RHIC,GSI)

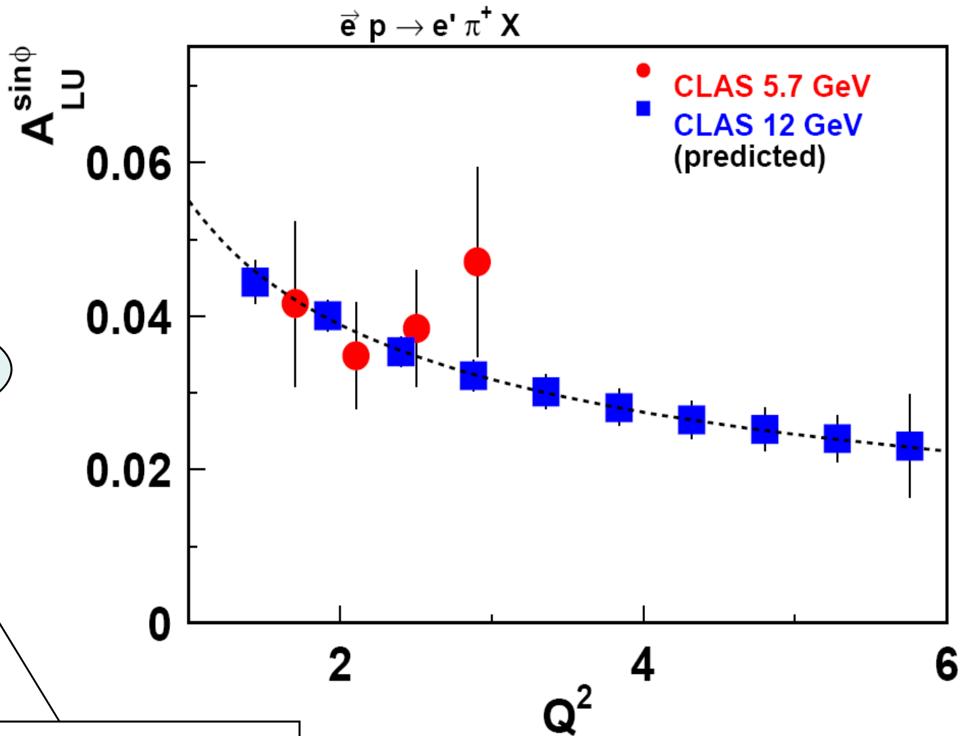
Beam SSA: CLAS @ 12 GeV

A_{LU}~ 1/Q (Twist-3)

$$A_{LU}^{\sin\phi} \propto g^{\perp}(x) D_1(z)$$

In jet limit A_{LU} dominated by twist-3 T-odd distribution





In the perturbative limit $1/P_T$ behavior expected

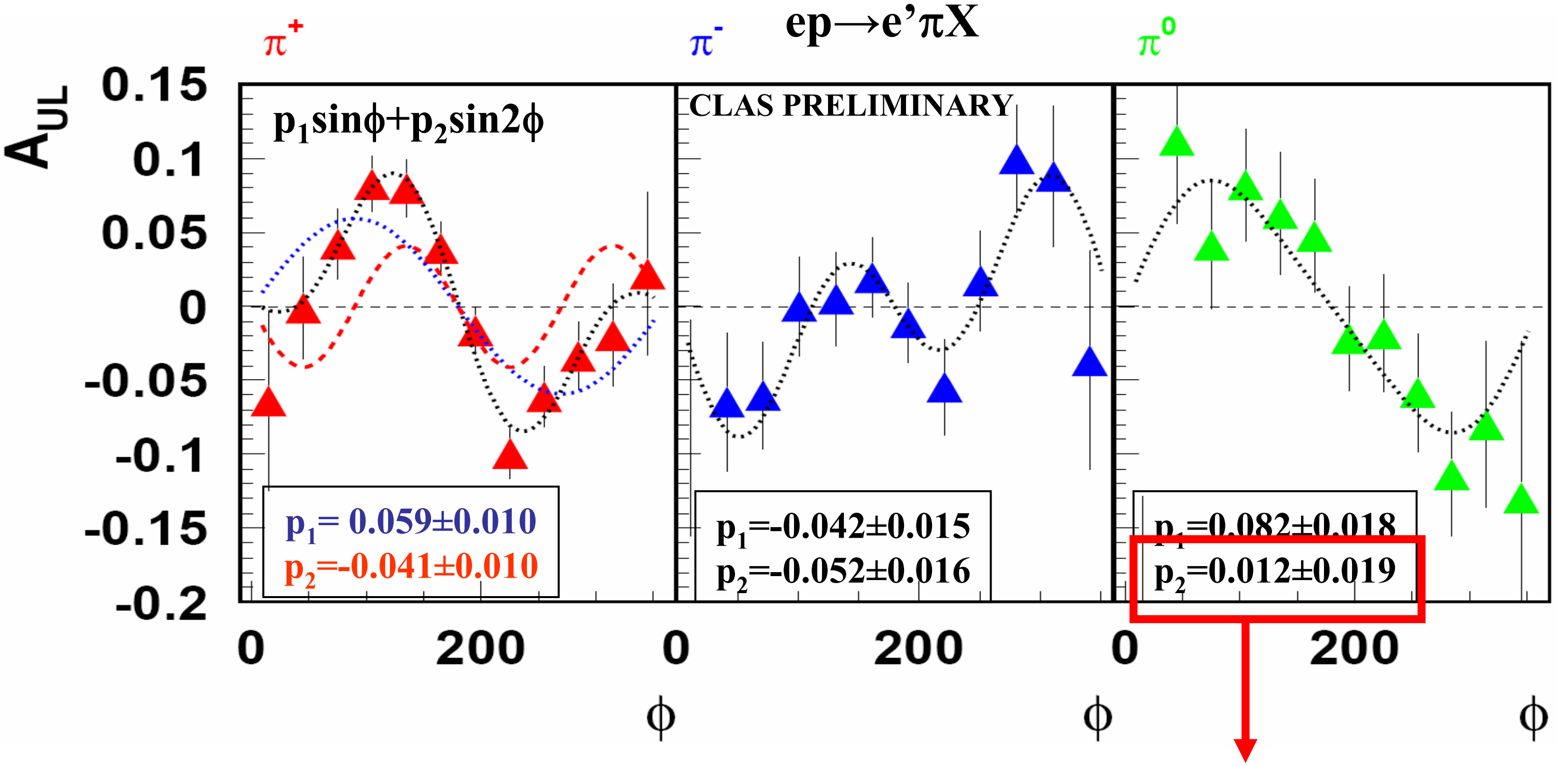
Measurements of kinematic (x, Q^2, z, P_T) dependences of beam SSA will provide a test of its HT nature and will probe HT distribution functions

Target SSA measurements at CLAS

$$A_{UL}(\phi) = \frac{1}{P_T}\frac{N^+ - N^-}{N^+ + N^-}$$

•Complete azimuthal coverage crucial for separation of sinϕ, sin2ϕ moments

$$A_{UL}^{\sin\phi} \propto \frac{zM}{Q} x f_L^{\perp} D_1$$



W²>4 GeV²
Q²>1.1 GeV²
y<0.85

0.4<z<0.7
M_X>1.4 GeV

P_T<1 GeV
0.12<x<0.48

No indication of Collins effect for π^0 (x20 more data expected)

Flavor decomposition of T-odd $f_L^\perp$ ($g^\perp$, $f_{1T}^\perp$)

In jet SIDIS with massless quarks contributions from $H_1^\perp$ vanish

$$\sigma_{UU} \propto \left(1 - y + y^2/2\right) \sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z)$$

$$\sigma_{UL}^{\sin\phi} \propto S_L \frac{M}{Q} y\sqrt{1-y} \sum_{q,\bar{q}} e_q^2 x f_L^{\perp q}(x) D_1^q(z) \longrightarrow \text{gauge link contribution}$$

With SSA measurements for $\pi^+ + \pi^-$ and π^0 on neutron and proton ($\pi = \pi^+ + \pi^-$) assuming $H^{fav} = H^{u\to\pi^+} \approx -H^{u\to\pi^-} = -H^{unfav}$

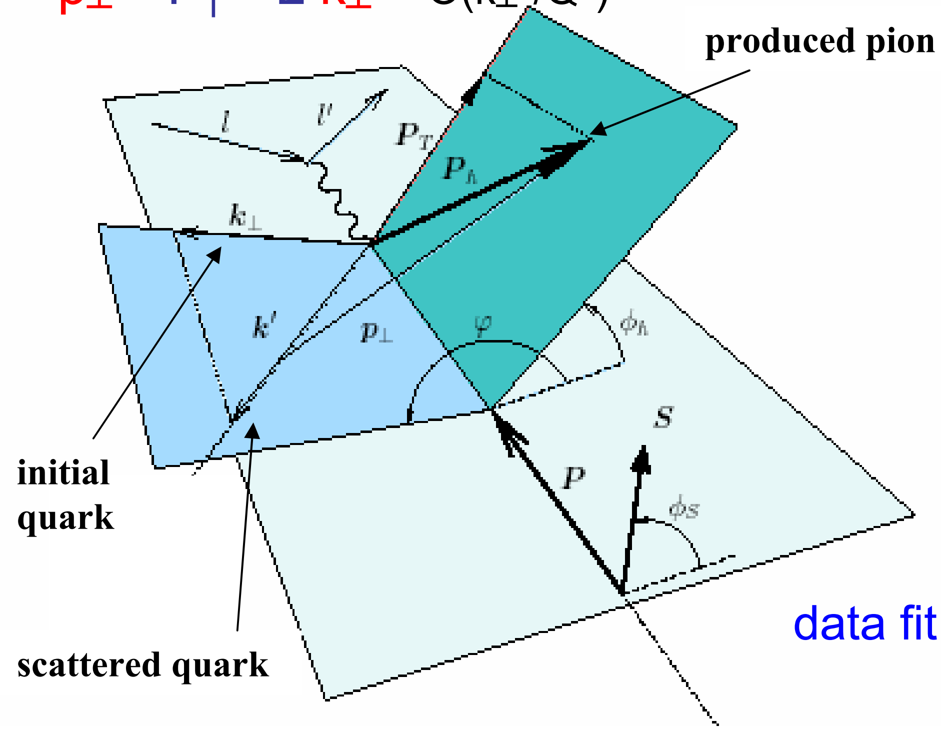
$$x f_L^{\perp u}(x) = \tfrac{4}{15}\left[A_{UL,p}^{\pi}(4u + d) - A_{UL,n}^{\pi}(d + u/4)\right]$$
$$x f_L^{\perp d}(x) = \tfrac{4}{15}\left[A_{UL,n}^{\pi}(4d + u) - A_{UL,p}^{\pi}(u + d/4)\right]$$

With $H_1^\perp(\pi^0) \approx 0$ (or measured) target and beam HT SSAs can be a valuable source of info on HT T-odd distribution functions

k_T-dependent SIDIS

$p_\perp = P_T - z\, k_\perp + O(k_\perp^2/Q^2)$

Anselmino et al (Phys.Rev D71,074006 (2005)



$$f_1^q(x) = \int d^2k_T\, f_1^q(x, k_T^2)$$

$$f_1^q(x,k_\perp) = f_1^q(x)\frac{1}{\pi\mu_0^2}\exp\left(-\frac{k_\perp^2}{\mu_0^2}\right),$$

$$D_q^h(z,p_\perp) = D_q^h(z)\frac{1}{\pi\mu_D^2}\exp\left(-\frac{p_\perp^2}{\mu_D^2}\right)$$

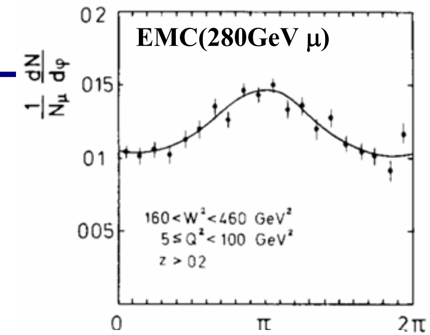
data fit on Cahn effect $\rightarrow \mu_0^2 = 0.25\,\mathrm{GeV}^2, \mu_D^2 = 0.2\,\mathrm{GeV}^2$

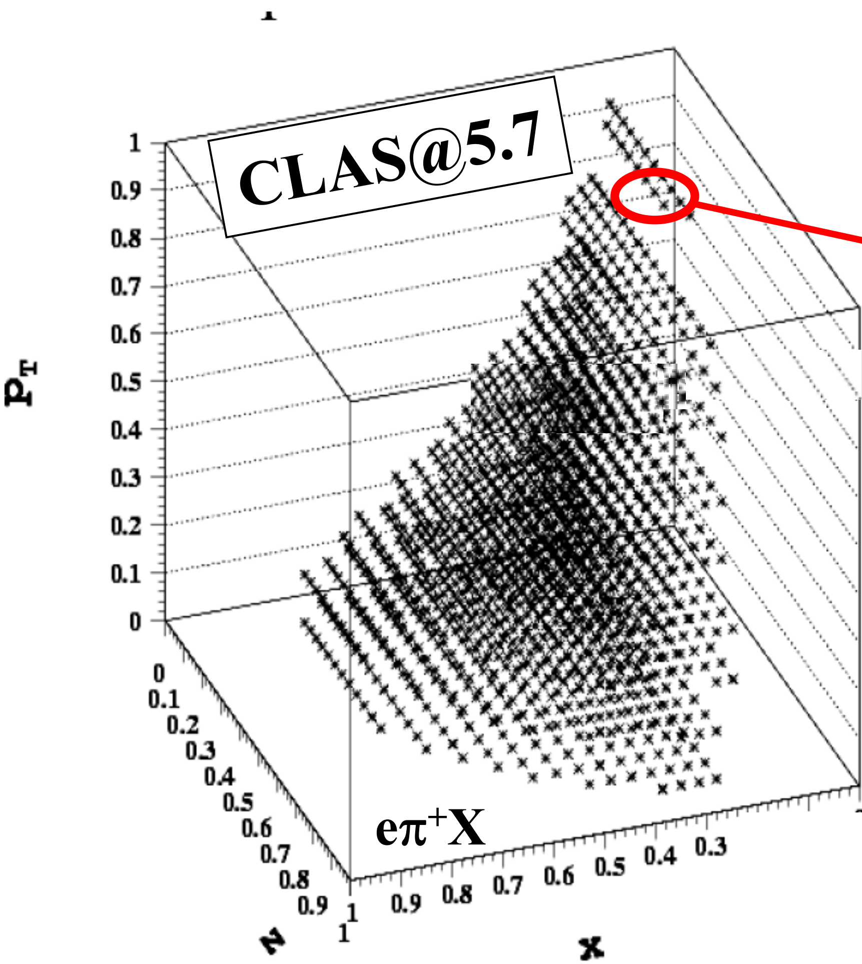
EMC (1987) and Fermilab (1993) data
(assuming $\mu_0^u = \mu_0^d$)

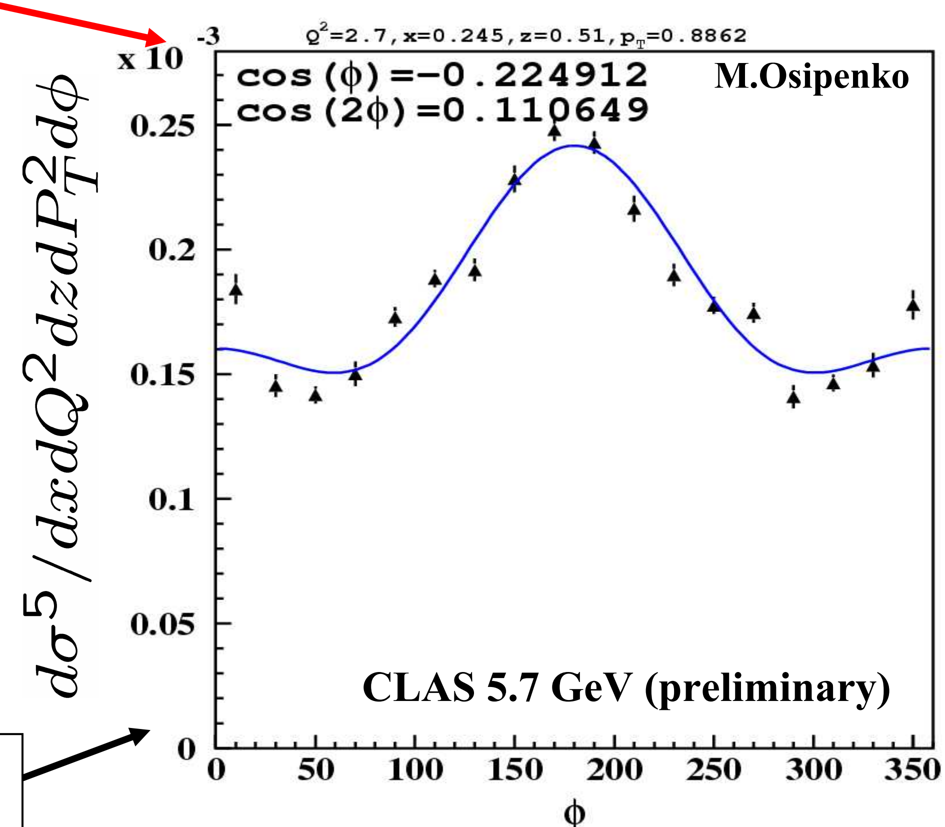
$$\sigma \sim \left[1 + (1-y)^2 - 4(2-y)\sqrt{1-y}\frac{z\mu_0^2|\mathbf{P}_{hT}|}{Q(\mu_D^2+\mu_0^2 z^2)}\cos\varphi_h\right]\frac{\exp\left(-\frac{\mathbf{P}_{hT}^2}{\mu_D^2+\mu_0^2 z^2}\right)}{\mu_D^2+\mu_0^2 z^2}\sum_q e_q^2\, f_1^q(x)\, D_q^h(z)$$

Precision measurements of azimuthal moments required to study kinematic and flavor dependences (μ_0^u and μ_0^d) of transverse momentum distributions of quarks

Unpolarized target azimuthal asymmetries







- Significant cosϕ, cos2ϕ observed at large P_T with CLAS at 5.7 GeV

Measurements of azimuthal moments in fine bins in x, Q^2, z and P_T for all pions will allow studies of flavor dependence of quark transverse momentum distributions.

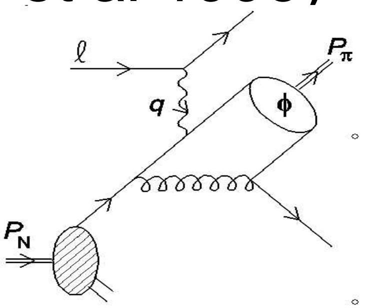
Azimuthal Asymmetries in SIDIS

- Intrinsic transverse momentum of partons (Cahn 1978)

$$-4\left(\frac{P_\perp^2}{Q^2}\right)^{\frac{1}{2}}\frac{a^2 z}{b^2+z^2a^2}\frac{(2-y)\sqrt{1-y}}{1+(1-y)^2}$$

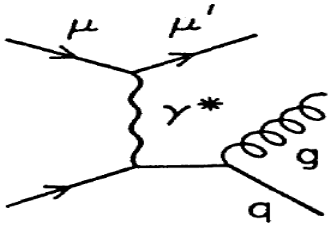
- Higher twists (Berger 1980, Brandenburg et al 1995)

$$2\left(\frac{P_\perp^2}{Q^2}\right)^{\frac{1}{2}}\frac{1}{3(1-z)}\frac{(2-y)\sqrt{1-y}}{1+(1-y)^2}$$



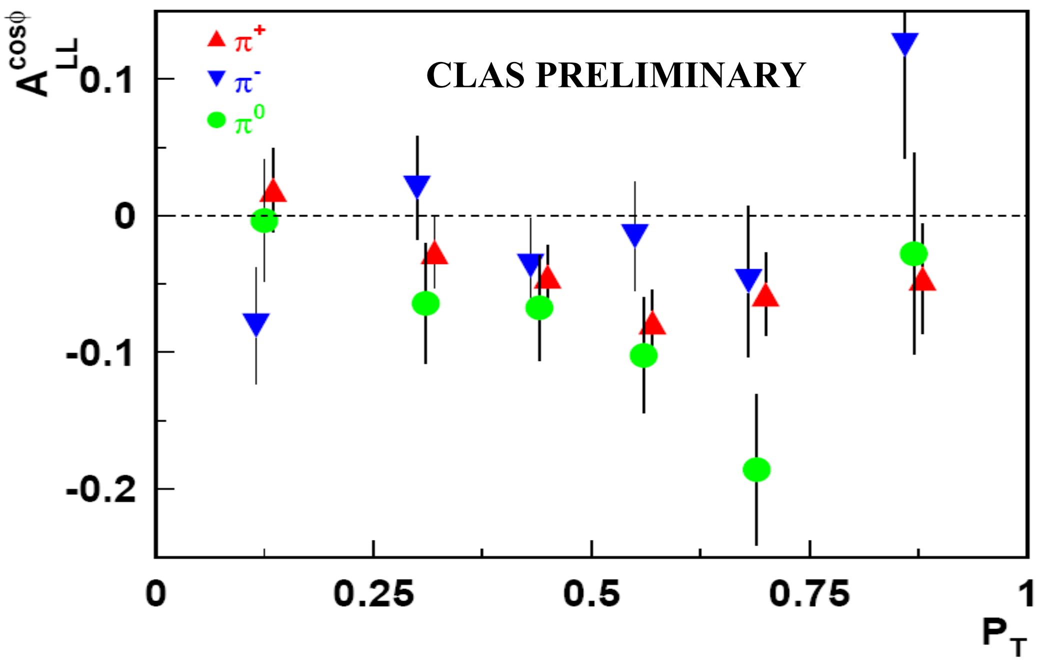
- Gluon bremsstrahlung (Georgi & Politzer, Mendez 1978) at z→1

$$-\frac{\alpha_s}{2}\sqrt{1-z}\frac{(2-y)\sqrt{1-y}}{1+(1-y)^2}$$

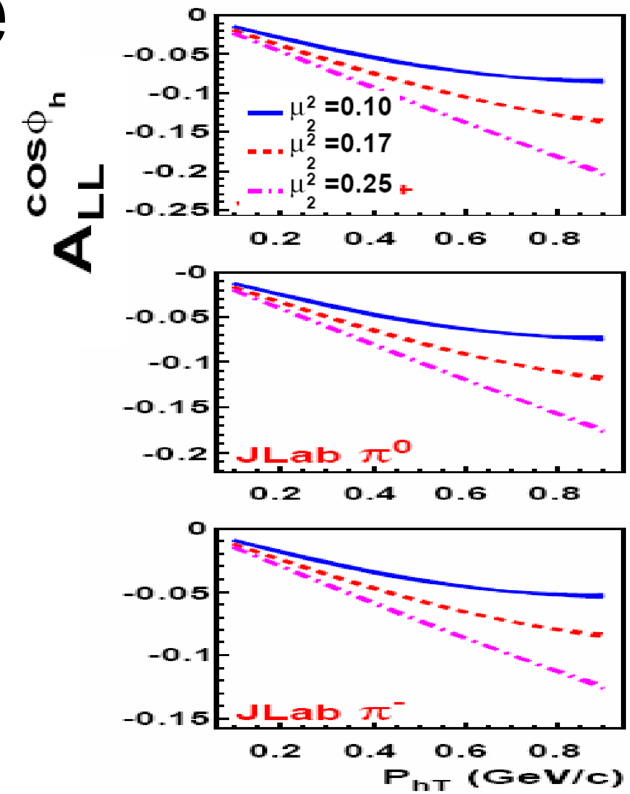


•Perturbative contribution negligible at low energies
•All known contributions to <cosϕ> and <cos2ϕ> are "flavor blind"

A_1-P_T-dependence



Anselmino et al. hep-ph/0608048



$$\sigma_0 = \frac{1+(1-y)^2}{xy^2}\,\frac{1}{\mu_D^2 + z^2\mu_0^2}\exp\left(-\frac{P_{hT}^2}{\mu_D^2+z^2\mu_0^2}\right)\sum_q e_q^2\, f_1^q(x)\, D_q^h(z)$$

$$\Delta\sigma_{LL}^{\cos\phi_h} = -4\,\frac{\sqrt{1-y}}{xy}\,\frac{z\,\mu_2^2\,P_{hT}}{Q\,(\mu_D^2+z^2\mu_2^2)^2}\exp\left(-\frac{P_{hT}^2}{\mu_D^2+z^2\mu_2^2}\right)\sum_q e_q^2\, g_1^q(x)\, D_q^h(z)$$

$$f_1^q(x,k_\perp) = f_1^q(x)\frac{1}{\pi\mu_0^2}exp(-\frac{k_\perp^2}{\mu_0^2})$$

$$g_1^q(x,k_\perp) = g_1^q(x)\frac{1}{\pi\mu_2^2}exp(-\frac{k_\perp^2}{\mu_2^2})$$

$$D_1^q(x,p_\perp) = g_1^q(x)\frac{1}{\pi\mu_D^2}exp(-\frac{p_\perp^2}{\mu_D^2})$$

Analysis of the polarized data, requires detailed knowledge of quark transverse momentum dependent distributions from unpolarized data

Summary

- Measurements of azimuthal moments in pion production in SIDIS provide important information on distributions of transverse momentum and polarization of quarks.
  - Measurement of Collins asymmetry with unpolarized and polarized targets provide access to leading twist chirall-odd distribution functions (Boer-Mulders and transversity distributions)
  - Measurement of Sivers function in a model independent way and study the FSI
  - SSA measurements in a wide range of Q^2, would allow studies of higher twist effects and probe T-odd distributions
  - SSA measurements in a wide range of P_T will allow to study the transition from non-perturbative to perturbative description.

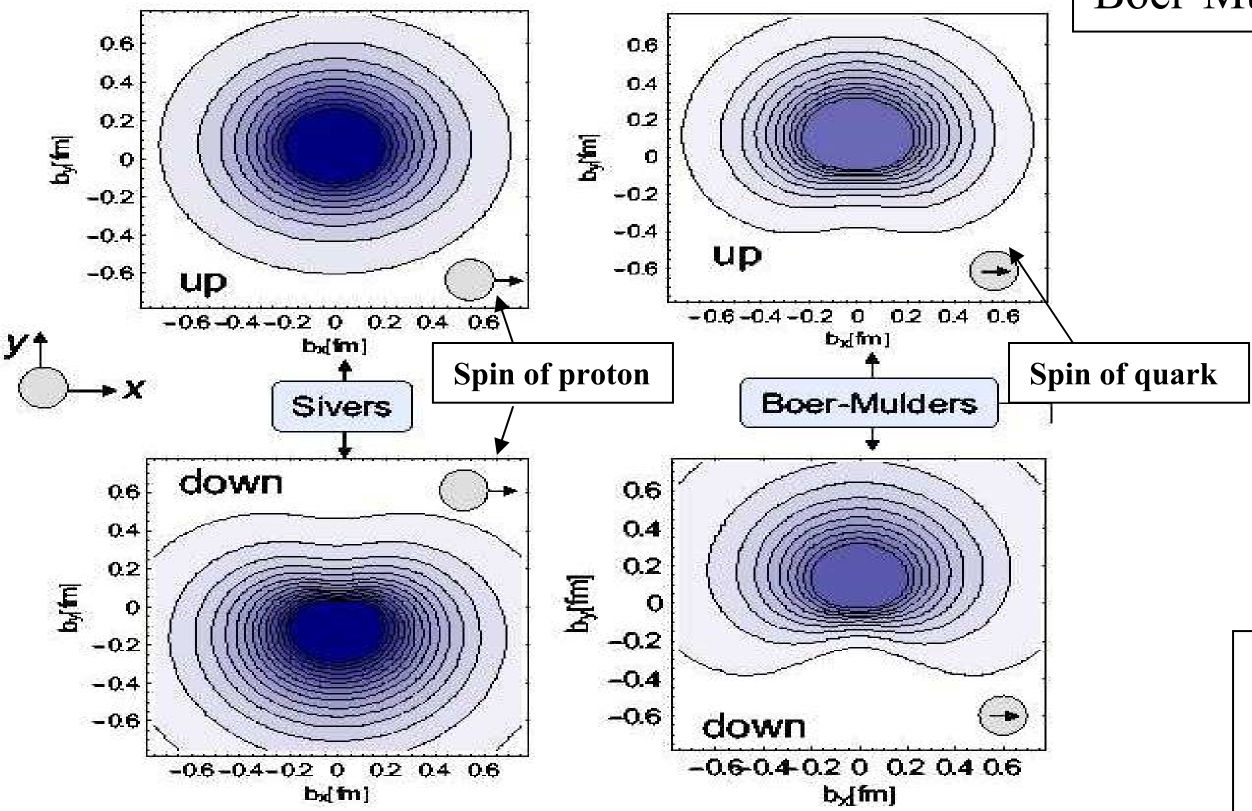
support slides…

BM-distribution and transversity GPDs

$2\tilde{H}_T + E_T$ **describe the sideways shift in distribution of transversely polarized quarks in the unpolarized proton** (Diehl,Haegler 2005)

$$-h_1^{\perp q} \sim \kappa_T^q = \int dx [2\tilde{H}_T(x,0,0) + E_T(x,0,0)]$$

Transverse spin-flavor dipole moment κ_T^q from GPDs related to Boer-Mulders TMD (Burkardt 2005)



Burkardt relation

$$\frac{h_1^{\perp q}}{2\tilde{H}_T + E_T} \sim \frac{f_{1T}^{\perp q}}{E}$$

GPDs

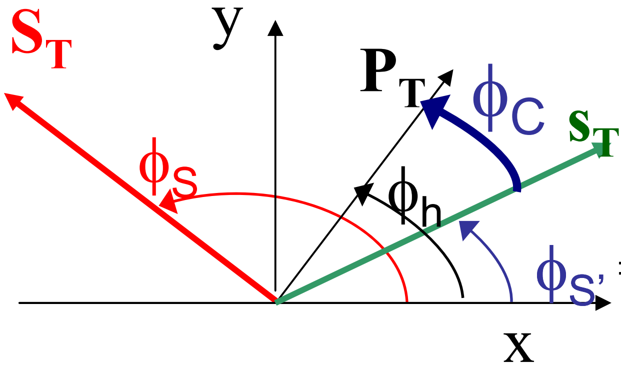
BM-function bigger than Sivers function ($1.5 \times f_{1T}^{\perp}$)

Both Lattice and GPD model calculations confirm large BM function!

Collins Effect: azimuthal modulation of the fragmentation function

$F_{UT} \propto h_1 H_1^{\perp}$

$s_T (q \times P_T) \leftrightarrow H_1^{\perp}$



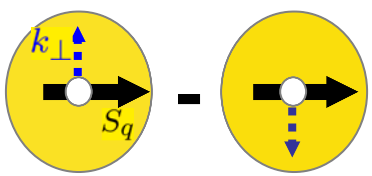
$\phi_{S'} = \pi - \phi_S$ ← spin of quark flips wrt y-axis

$$D(z,P_T) = D_1(z,P_T) + H_1^{\perp}(z,P_T)\,\sin(\underbrace{\phi_h - \phi_{S'}}_{\phi_C})$$

$\Rightarrow \sin(\phi_h + \phi_S)$

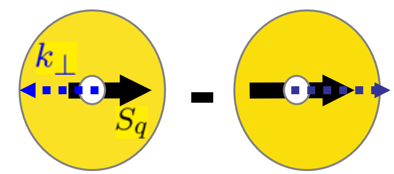
$F_{UU} \propto h_1^{\perp} H_1^{\perp}$

$s_T (p \times k_T) \leftrightarrow h_1^{\perp}$

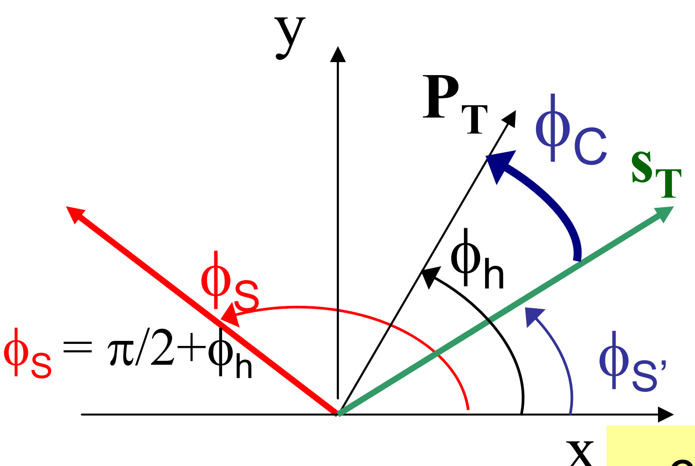


$F_{UL} \propto h_{1L}^{\perp} H_1^{\perp}$

$(s_T k_T)(p S_L) \leftrightarrow h_{1L}^{\perp}$

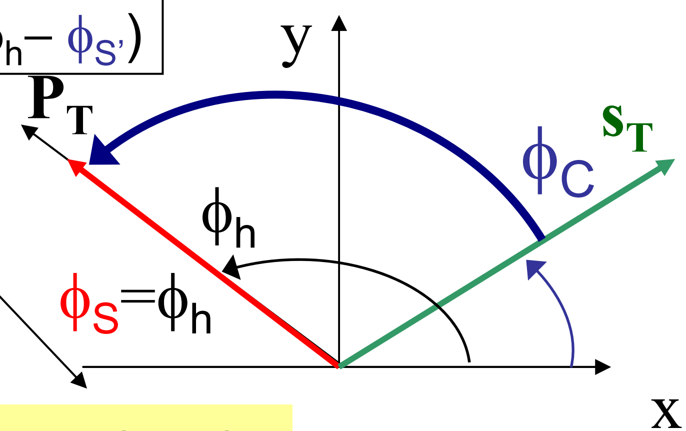


$\sin\phi_C = \sin(\phi_h - \phi_{S'})$



$\cos(2\phi_h)$

$\phi_{S'} = \pi - \phi_S = \pi/2 - \phi_h$

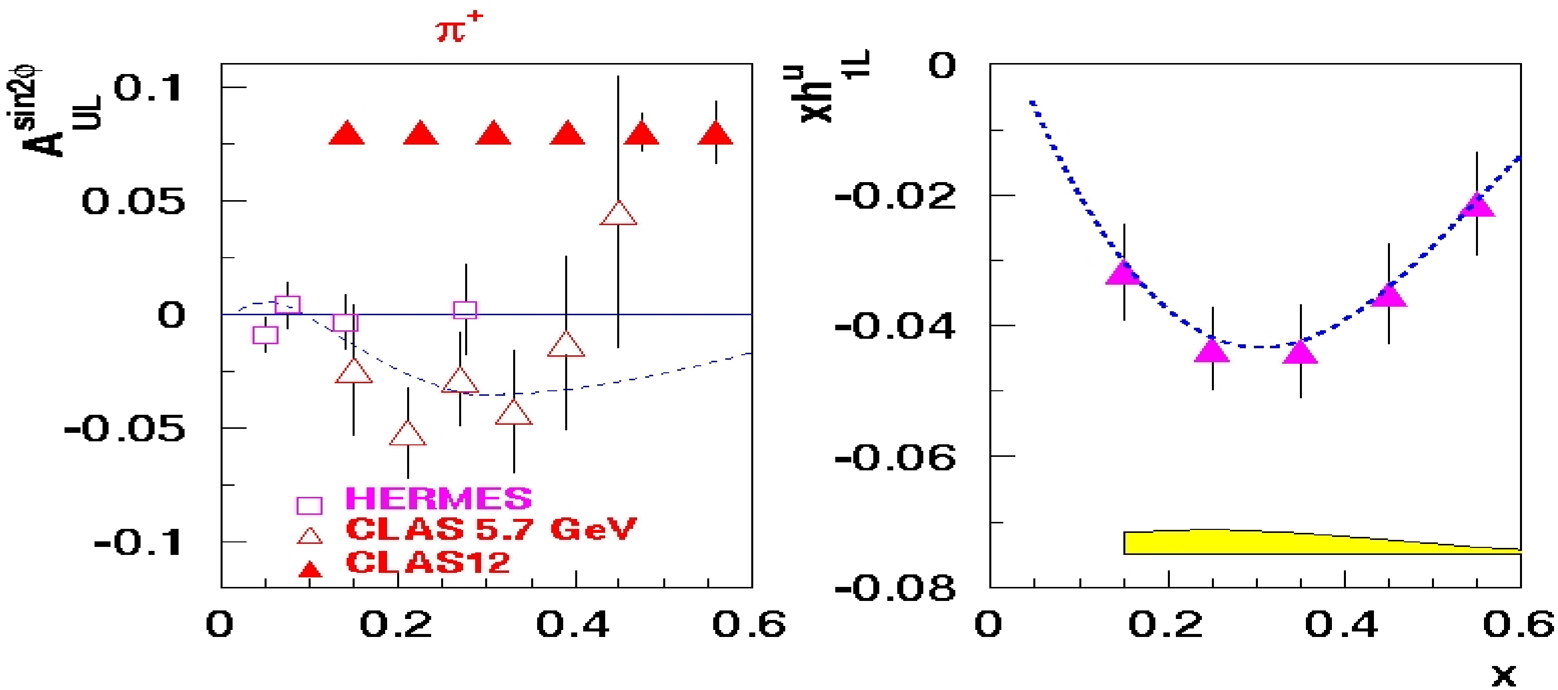


$\sin(2\phi_h)$

$\phi_{S'} = \pi - \phi_S = \pi - \phi_h$

CLAS12: Mulders TMD projections

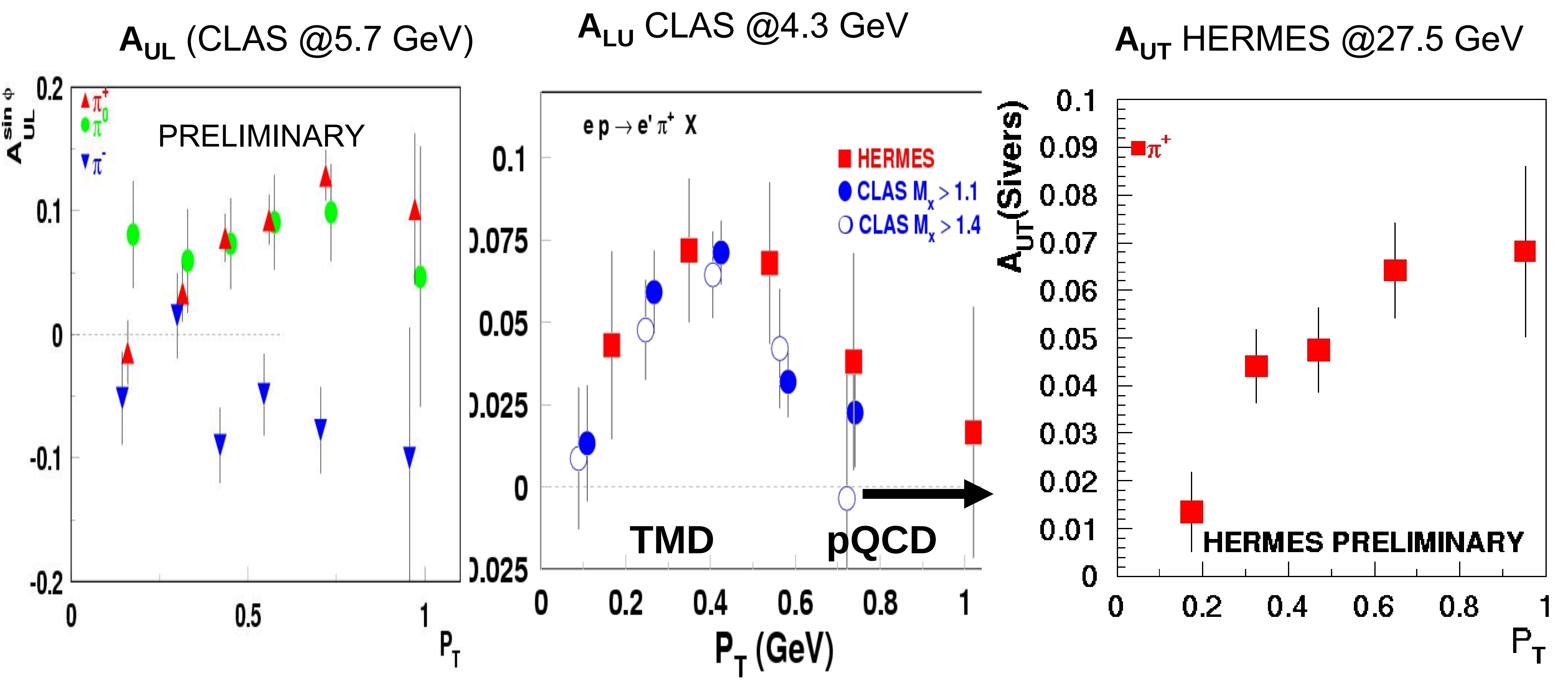
$$\sigma_{UL}^{KM} \sim (1-y) h_{1L}^{\perp} H_1^{\perp}$$



Simultaneous measurement of, exclusive ρ,ρ+,ω with a longitudinally polarized target important to control the background.

SSA: P_T-dependence of sinϕ moment

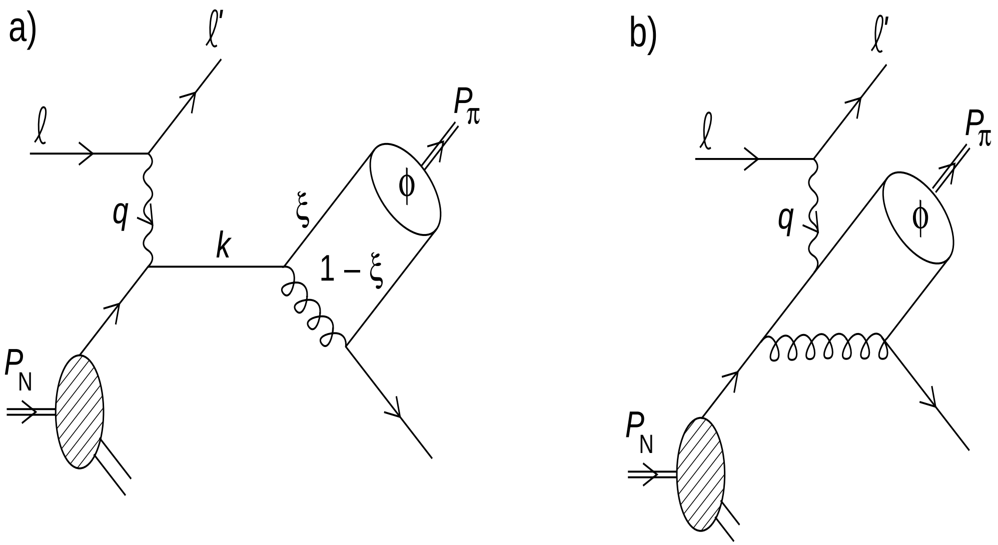
$\sigma^{\sin\phi}_{LU(UL)} \sim F_{LU(UL)} \sim 1/Q$ (Twist-3)

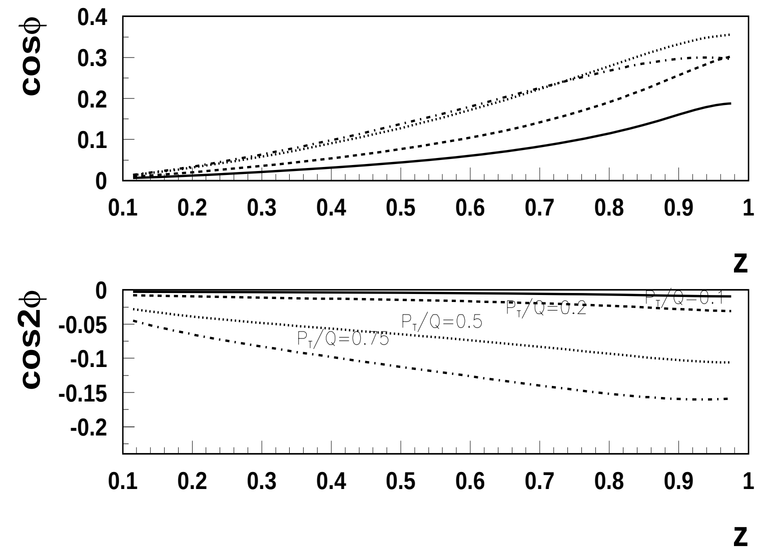


Beam and target SSA for π+ are consistent with increase with P_T
In the perturbative limit is expected to behave as $1/P_T$

Azimuthal Asymmetries in semi-exclusive limit

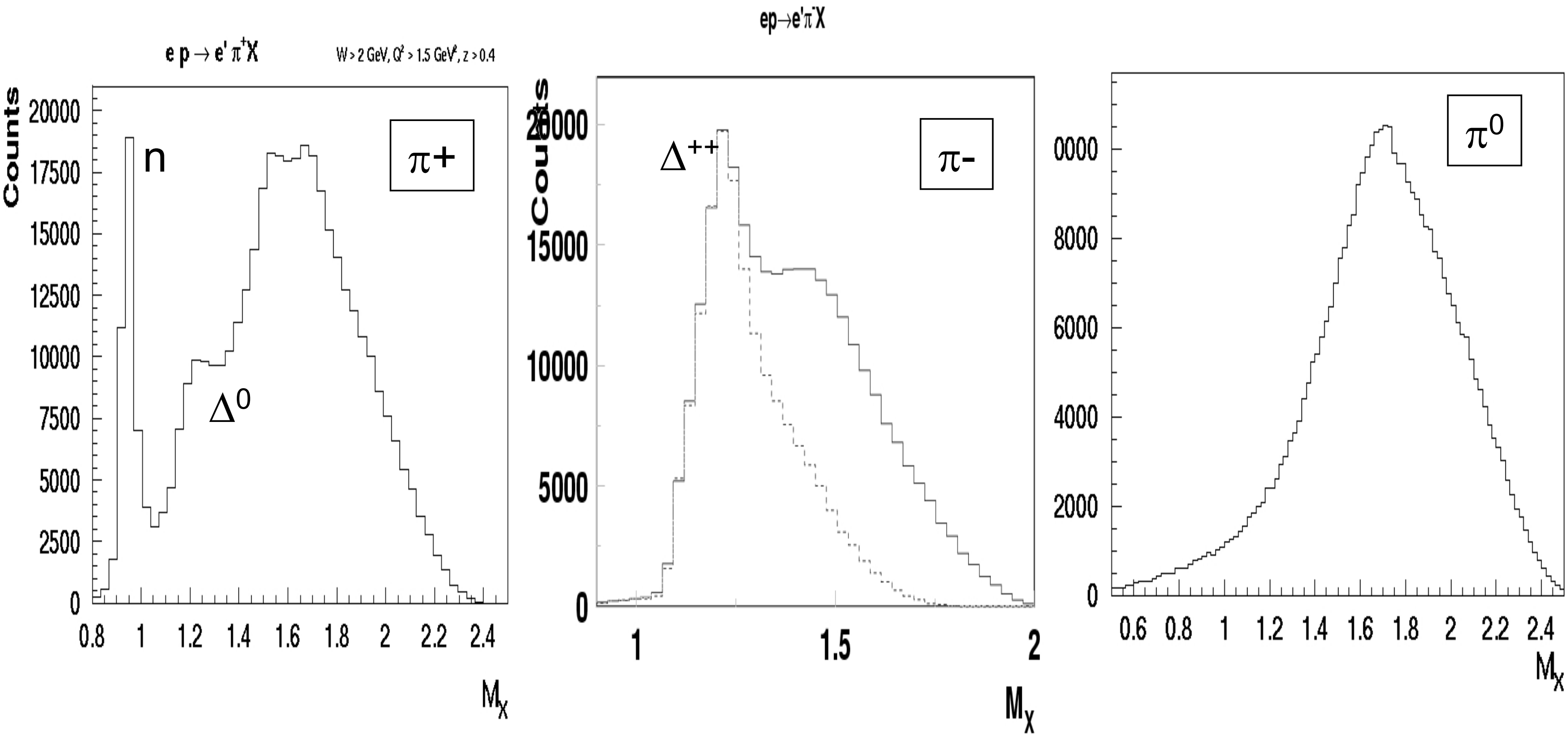
- Higher twists (Berger 1980, Brandenburg et al 1995) $z \to 1$ dominant contribution $u + e^- \to e^- \pi^+ d$





Dominant contribution to meson wave function is the perturbative one gluon exchange and approach is valid at factor ~3 lower Q^2 than in case of hard exclusive scattering (Afanasev & Carlson 1997)

Missing mass of pions in ep->e'πX

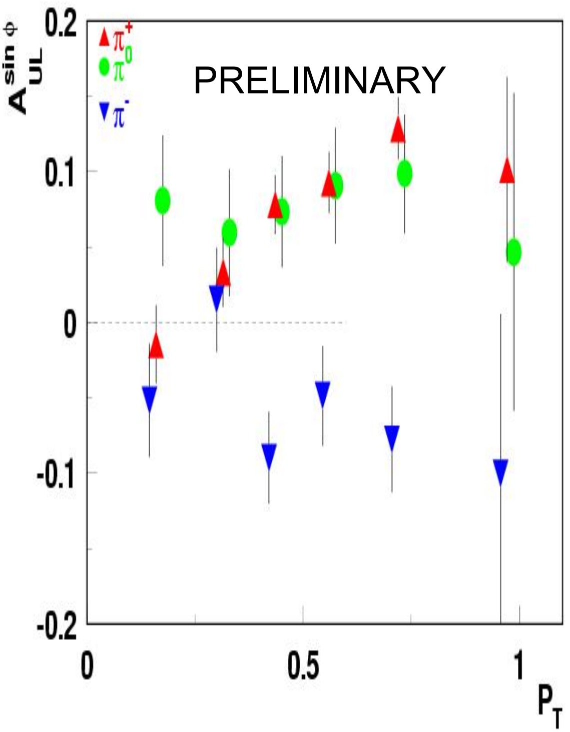


Large Delta(1232) contribution makes π- different (M_x>1.5 GeV applied)

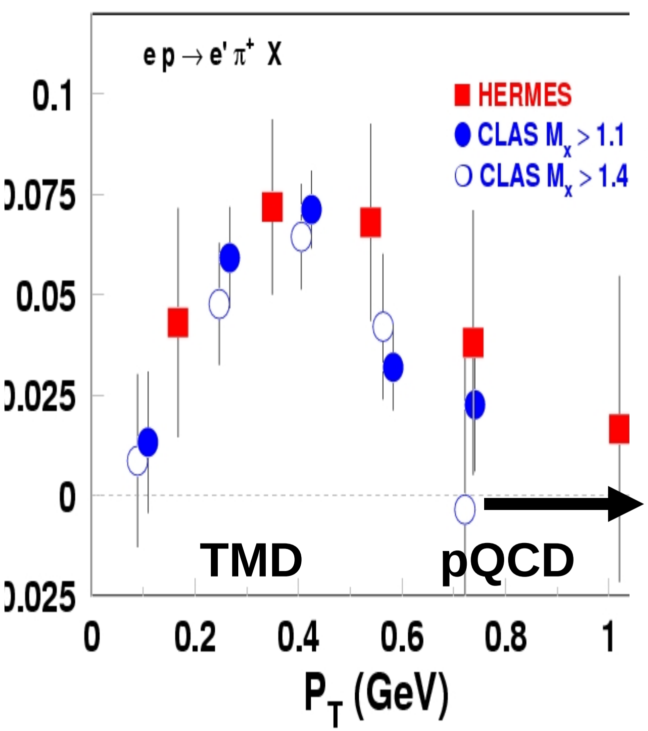
SSA: P_T-dependence of sinϕ moment

$\sigma^{\sin\phi}_{LU(UL)} \sim F_{LU(UL)} \sim 1/Q$ (Twist-3)

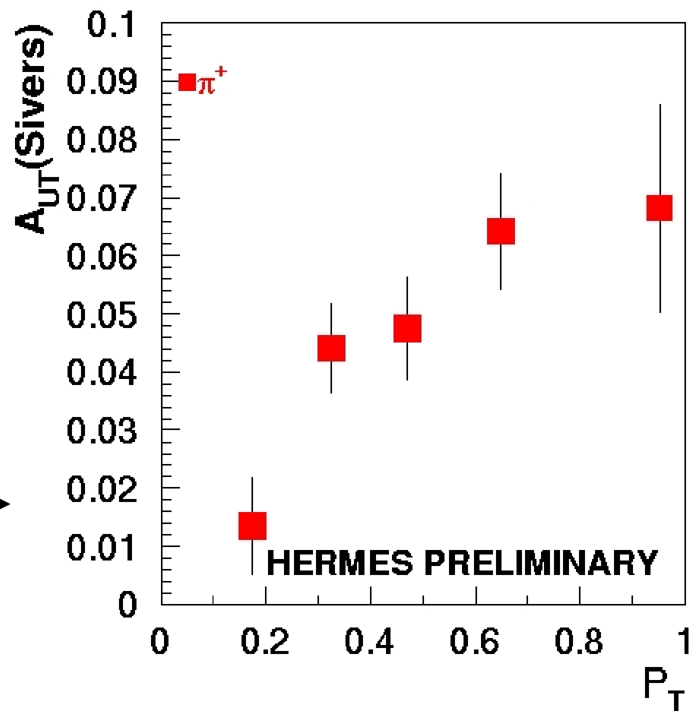
A_{UL} (CLAS @5.7 GeV)



A_{LU} CLAS @4.3 GeV



A_{UT} HERMES @27.5 GeV



$$A_{UL}^{\sin\phi} \propto f_L^{\perp} D_1$$

$$A_{UL}^{\sin\phi} \propto g^{\perp} D_1$$

$$A_{UT}^{\sin\phi} \propto f_{1T}^{\perp} D_1$$

Beam and target SSA for π+ are consistent with increase with P_T
In the perturbative limit is expected to behave as $1/P_T$

Higher Twist SSAs

Target sinϕ SSA (Bacchetta et al. 0405154)

Discussed as main sources of SSA due to the Collins fragmentation

$$A_{UL}^{\sin\phi} \approx \frac{2(2-y)\sqrt{1-y}}{(1-y+y^2) f_1 D_1} \frac{z M M_h}{Q} \left[-\frac{M}{M_h} x f_L^{\perp(1)} D_1 - x h_L H_1^{\perp(1)} - \frac{M_h}{M} g_1 \frac{G^{\perp(1)}}{z} - h_{1L}^{\perp(1)} \frac{\tilde{H}}{z} \right]$$

In jet SIDIS only contributions ~ D_1 survive

The same unknown fragmentation function

Beam sinϕ SSA

$$A_{LU}^{\sin\phi} \approx \frac{2y\sqrt{1-y}}{(1-y+y^2) f_1 D_1} \frac{z M M_h}{Q} \left[\frac{M}{M_h} x g^{\perp(1)} D_1 + x e H_1^{\perp(1)} - \frac{M_h}{M} f_1 \frac{G^{\perp(1)}}{z} - h_1^{\perp(1)} \frac{E}{z} \right]$$

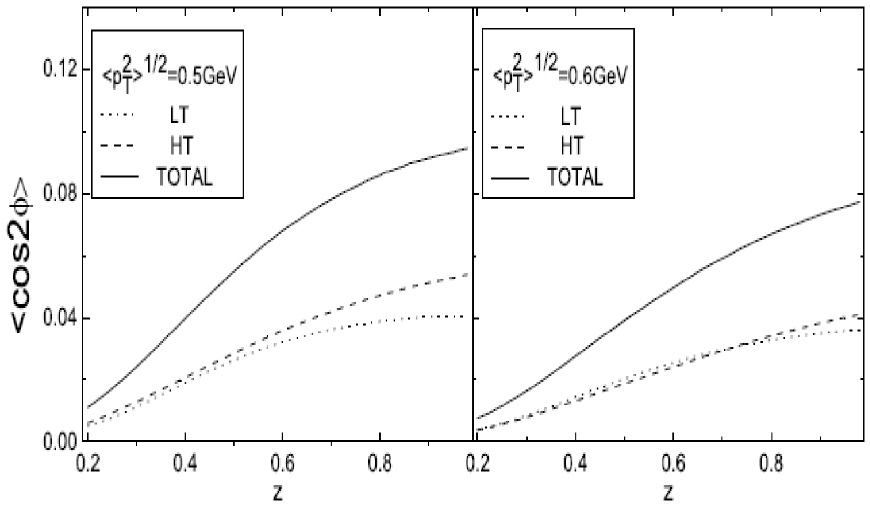
With $H_1^{\perp}(\pi^0)\approx 0$ (or measured) Target and Beam SSA can be a valuable source of info on HT T-odd distribution functions

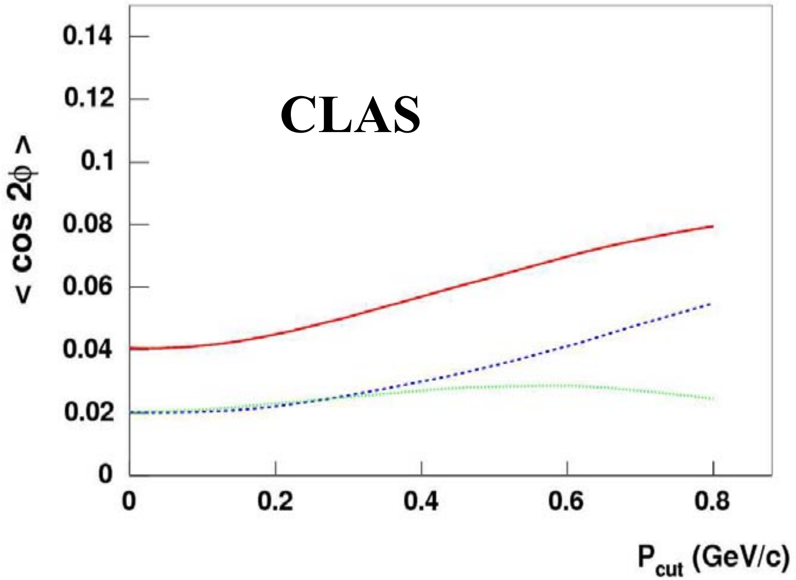
Azimuthal moments in SIDIS (1/Q^2)

$$\frac{d^5\sigma^{\ell p\to\ell hX}}{dx_B\,dQ^2\,dz_h\,d^2\mathbf{P}_T} \simeq \sum_q \frac{2\pi\alpha^2 e_q^2}{Q^4}\; f_q(x_B)\; D_q^h(z_h)\Big[1+(1-y)^2 + \frac{4\mu_0^2(1-y)}{\mu_H^2 Q^2}(\mu_D^2 + \frac{z^2\mu_0^2 P_T^2}{\mu_H^2}) - 4\,\frac{(2-y)\sqrt{1-y}\,\mu_0^2\,z_h\,|\vec{P_T}|}{\mu_H^2\,Q}\;\cos\phi_h + \frac{4\mu_0^4 z^2(1-y)P_T^2}{\mu_H^4 Q^2}\cos 2\phi_h\Big]\frac{1}{\pi\mu_H^2}\,e^{-P_T^2/\mu_H^2}\;,$$

cos2ϕ: predictions

V.Barone





BM is the only mechanism with sign change from π+ to π-

- **Significant asymmetry predicted for HERMES and CLAS**
- **Asymmetry is LT! (not decreasing with 1/Q)**

DY-experiments

$$\pi^- + N \rightarrow \gamma^* + X \rightarrow \mu^+ + \mu^- + X$$

NA10(1986) **194-GeV π- tungsten target (145000 events)**

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \sim 1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\,.$$

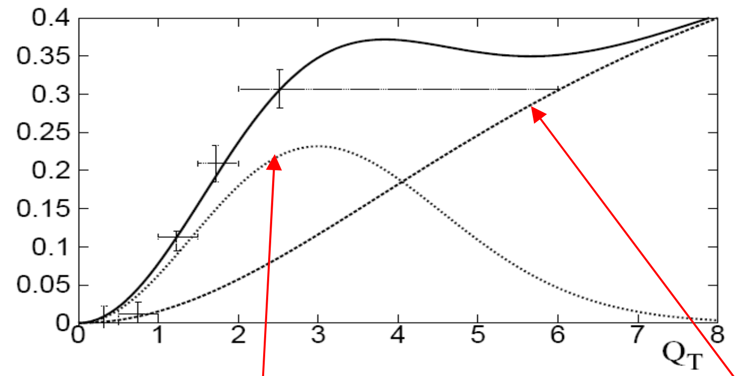


Figure 3. *Impression* of possible contributions to ν as function of Q_T compared to DY data of NA10 (for $Q = 8$ GeV). Dashed curve: contribution from perturbative one-gluon radiation. Dotted curve: contribution from a nonzero $h_1^\perp$. Solid curve: their sum.

$$h_1^{\perp a}(x, p_T^2) = \frac{\alpha_T}{\pi}\, c_H^a\, \frac{M_C M_H}{p_T^2 + M_C^2}\, e^{-\alpha_T p_T^2}\, f_1(x), \qquad (50)$$

with $M_C = 2.3$ GeV, $c_H^a = 1$ and $\alpha_T = 1\,\mathrm{GeV}^{-2}$, which can be used to get rough estimates for other asymmetries.

E615 Fermilab 80-GeV π-, 252-GeV π+ (1989) – 36000 muon pairs

SIDIS moments: E665

find that most of the observed asymmetry arises from intrinsic transverse momentum consistent with the conclusions of the EMC analysis.

E665 experiment (490 GeV μp-12k, μd-49k)

$$60 < \nu < 500\text{GeV} \; ,$$

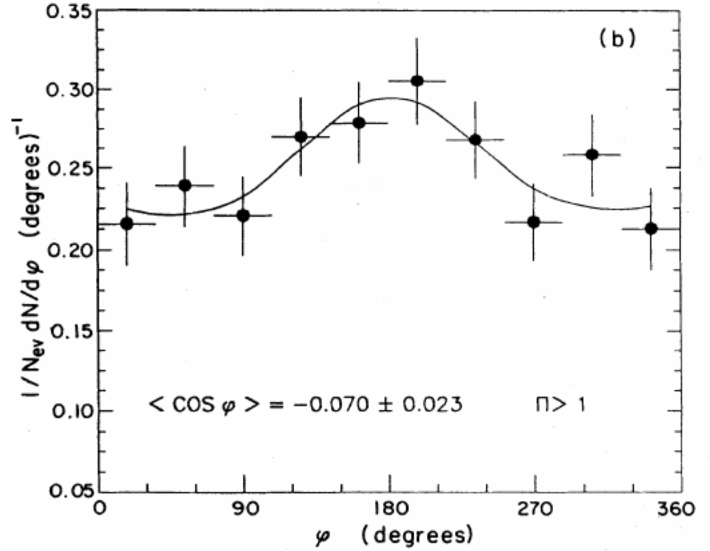
$$Q^2 > 3.0\text{GeV}^2/c^2 \; ,$$

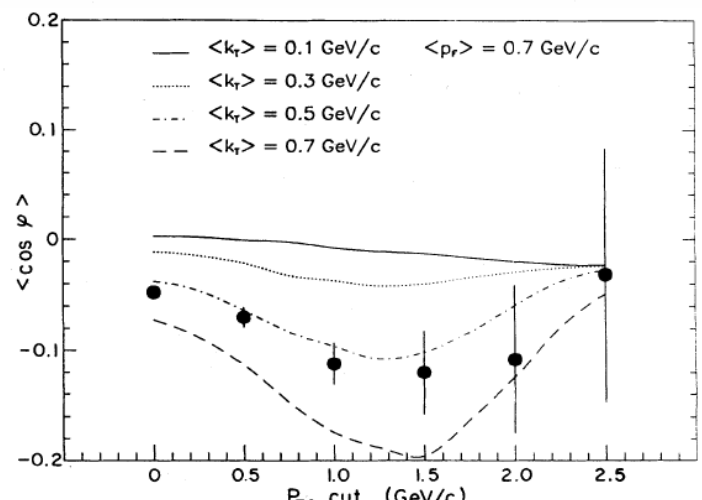
$$0.1 < y_{\text{Bj}} < 0.85 \; ,$$

$$100 < W^2 < 900\text{GeV}^2/c^4$$

$$x_{\text{Bj}} > 0.003 \; .$$

$$\Pi = \frac{4}{\sqrt{n_H}} \sum (|p_T| - p_{T^0})$$





SIDIS moments: EMC(1986)

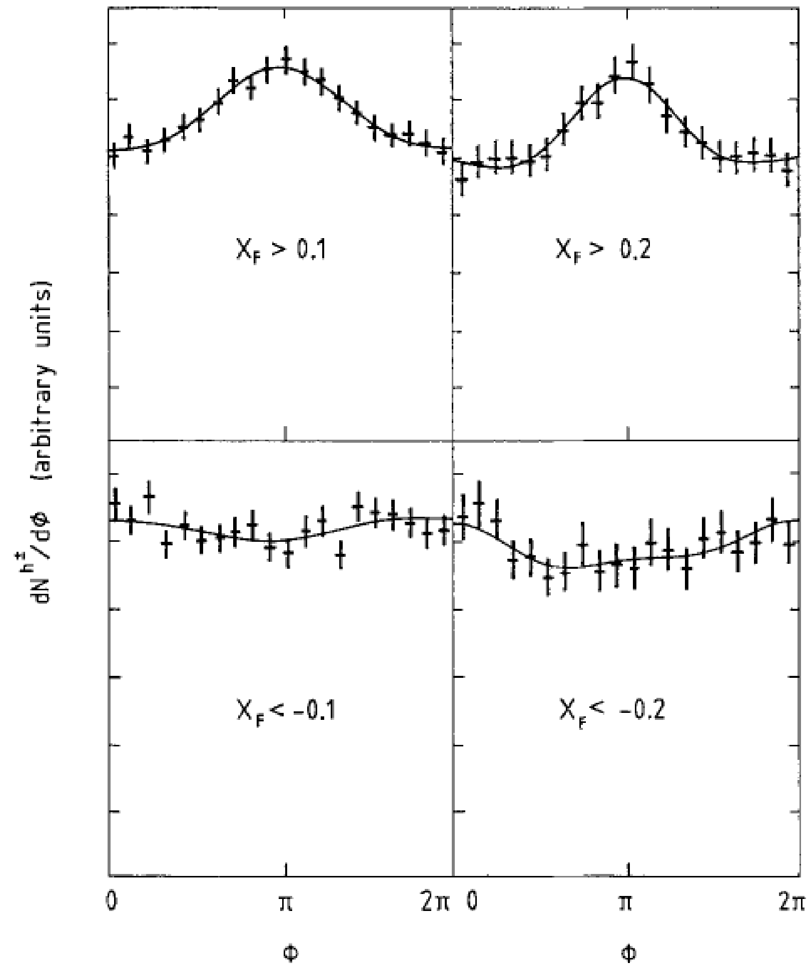
EMC experiment (280 GeV μp-27k)

280 GeV were incident on a 1 m long liquid hydrogen target

$Q^2 > 4\ GeV^2$, $40 < W^2 < 450\ GeV^2$, $\nu > 20$ (

$y < 0.8$

the model. Variations of the parameters of the model indicate that hard QCD processes contribute only a small amount to the non-zero $\langle \cos\phi \rangle$, while a value of $\langle K_T^2 \rangle \geq (0.44\ \text{GeV})^2$ was indicated for the intrinsic K_T of the struck quark. The relatively minor contribution of hard QCD processes to the non-zero $\langle \cos\phi \rangle$ was also suggested by studies of $\langle \cos\phi \rangle$ as a function of p_T. The values of $\langle \cos 2\phi \rangle$ and $\langle \sin\phi \rangle$



SIDIS moments: ZEUS(1999)

ZEUS experiment (38pb-1 ~7700 ev)

Figure 4 compares the data with two LO QCD calculations. Both calculations were made with Q as the appropriate scale, with the Binnewies et al. LO fragmentation function [31] and with the CTEQ4 LO proton parton densities [24]. The LO calculations result in a qualitatively similar behaviour to the LEPTO and ARIADNE Monte Carlo generator predictions.

The analytic calculation from ZEUS (based on the calculation of Chay et al. [5]) includes an estimation of the non-perturbative contribution, from intrinsic k_T and hadronisation p_T, and integrates over the whole kinematic range. The results of Ahmed & Gehrmann are purely perturbative at leading order in α_s and are evaluated at the mean values $\langle x \rangle = 0.022$ and $\langle Q^2 \rangle = 750$ GeV^2 of the data. The different implementations account for the observed difference in the two predictions; using $\langle x \rangle$ and $\langle Q^2 \rangle$ in the ZEUS perturbative calculation leads to agreement with the Ahmed & Gehrmann calculation.

Systematics

The major systematic errors can be divided into three types: uncertainties due to event reconstruction and selection; to track selection; and to the modelling of the hadronic system. No single systematic uncertainty was larger than the statistical error in the mean of either $\cos\phi$ or $\cos 2\phi$. For both mean values, the largest effects, which approached the statistical uncertainties, were associated with: the inclusion of tracks not associated with the primary vertex; the use

kinematic region studied is $0.2 < y < 0.8$ and $0.01 < x < 0.1$, corresponding to a Q^2 range $180 < Q^2 < 7220$ GeV^2.

$0.2 < z_h < 1.0$

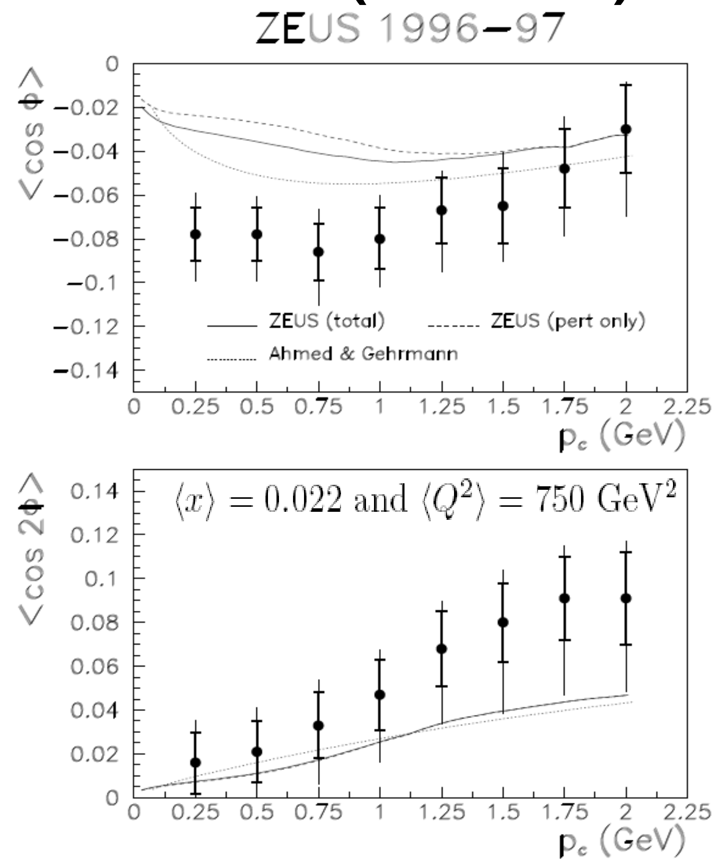


Figure 4: The values of $\langle\cos\phi\rangle$ and $\langle\cos 2\phi\rangle$ are shown as a function of p_c in the kinematic region $0.01 < x < 0.1$ and $0.2 < y < 0.8$ for charged hadrons with $0.2 < z_h < 1.0$. The inner error bars represent the statistical errors, the outer are statistical and 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.