SIDIS with CLAS12

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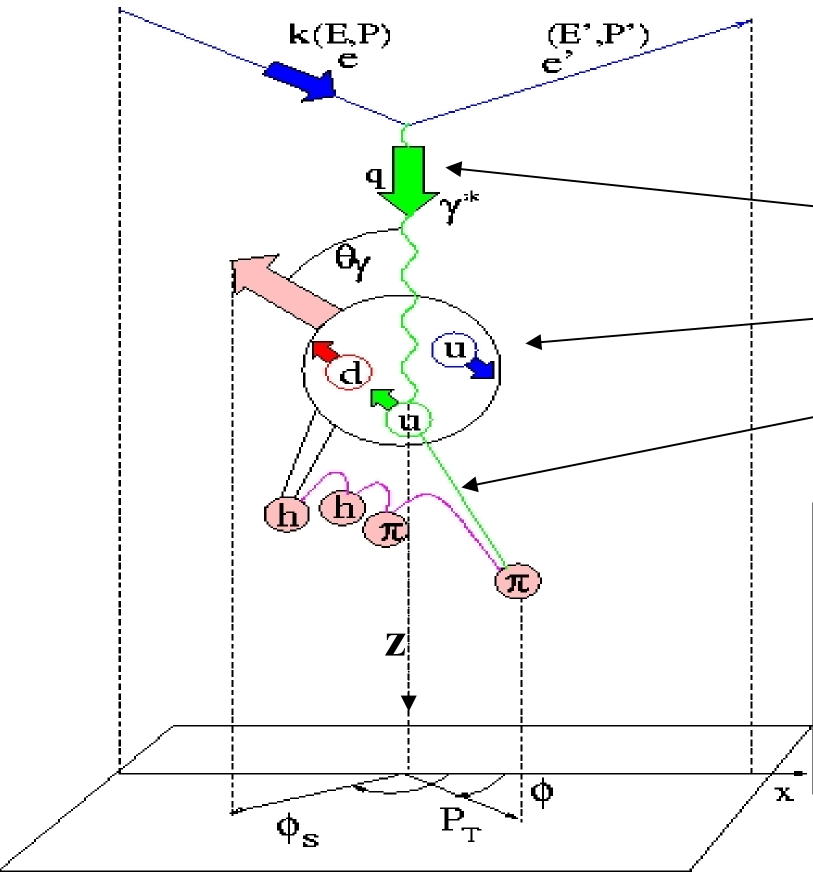
Inclusive and Semi-Inclusive Spin Physics Workshop, Dec 14 JLab

Physics motivation
k_T-effects and Collins asymmetry
TMD studies from unpolarized target data
TMD studies from polarized target data
Target fragmentation
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*

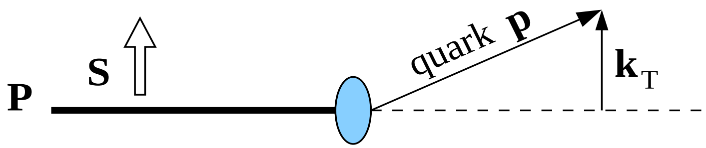
$$\nu = E - E'$$
$$y = \nu / E$$
$$x = Q^2 / 2M\nu$$
$$z = E_h / \nu$$

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.

Transverse momentum of quarks



$\mathbf{p} = x\mathbf{P} + \mathbf{k}_T$

Mulders & Tangerman (twist-2)

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Boer-Mulders

Sivers

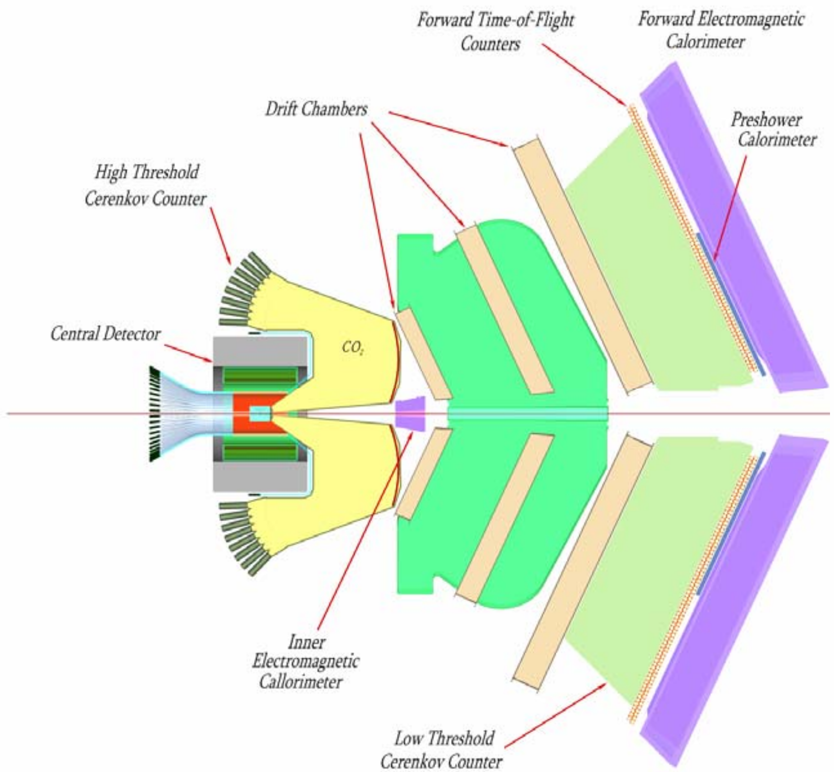
Transversity

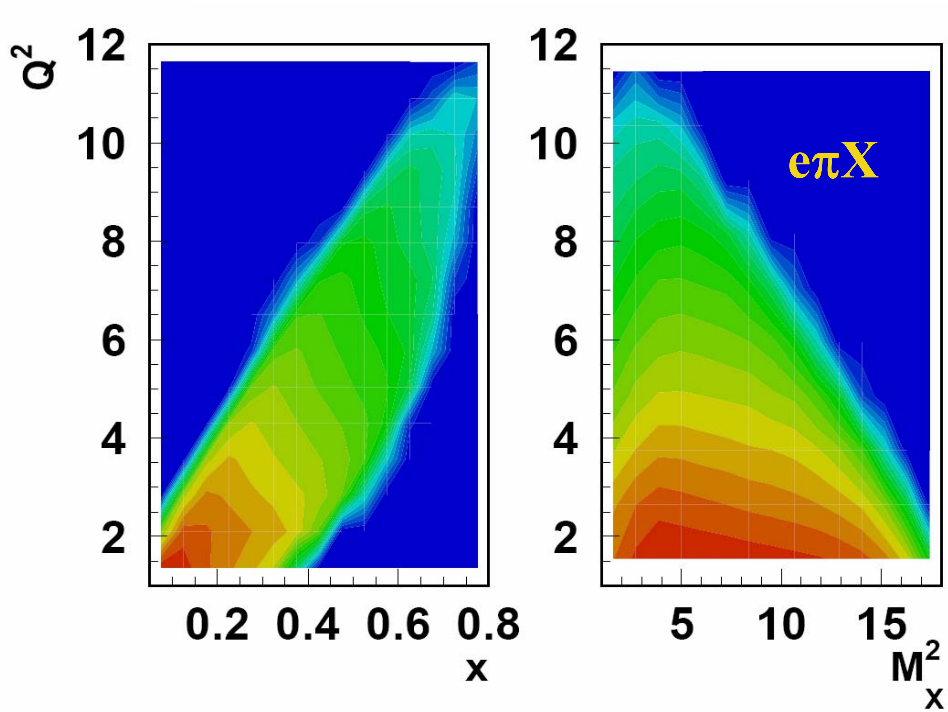
Off diagonal PDFs related to interference between L=0 and L=1 light-cone wave functions.

- k_T – **required to describe azimuthal distributions of hadrons and in particular SSAs.**
- k_T - **important for cross section description (also for exclusive production)**
  - P_T distributions of hadrons in DIS
  - exclusive photon production (DVCS)
  - hard exclusive vector meson production
- k_T – **leads to 3D description with 8PDFs**

- Gauge invariant definition of k_T-dependent PDFs introduced
- Universality of k_T-dependent distribution and fragmentation functions proven. Sign flip for $f_{1T}^\perp$, $h_1^\perp$ from DY to SIDIS predicted.
- Factorization proven for small k_T.

CLAS12: Kinematical coverage





Track resolution:

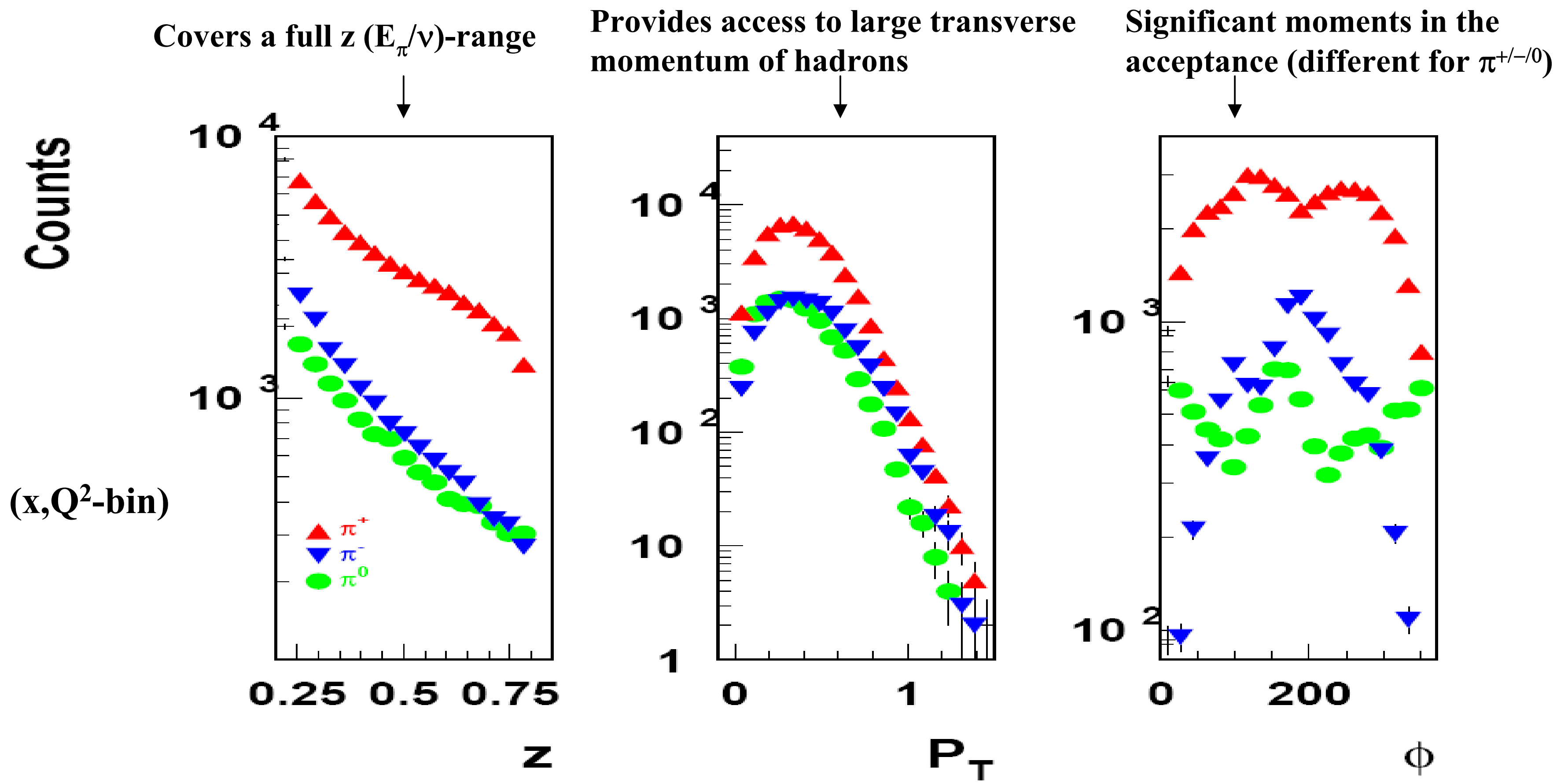
δp (GeV/c)		$0.003p + 0.001p^2$
δq (mr)	<	1
δϕ (mr)	<	3

SIDIS kinematics

$Q^2>1$
$W^2>4$
$y<0.85$
$M_X>2$

Large Q^2 accessible with CLAS12 are important for separation of HT contributions

CLAS12: kinematic distributions using LUND-MC



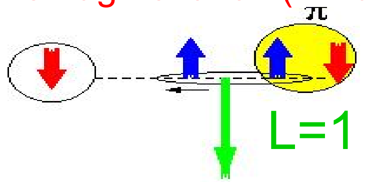
Wide kinematical coverage of CLAS12 allows fine binning in all relevant kinematical variables for all 3 pions.

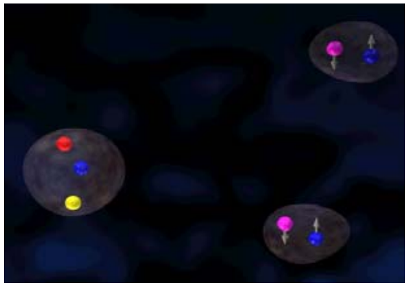
Collins effect

$$\mathbf{D(z)\rightarrow D_1(z)+H_1^{\perp}(z)\ \sin(\phi_C)}$$

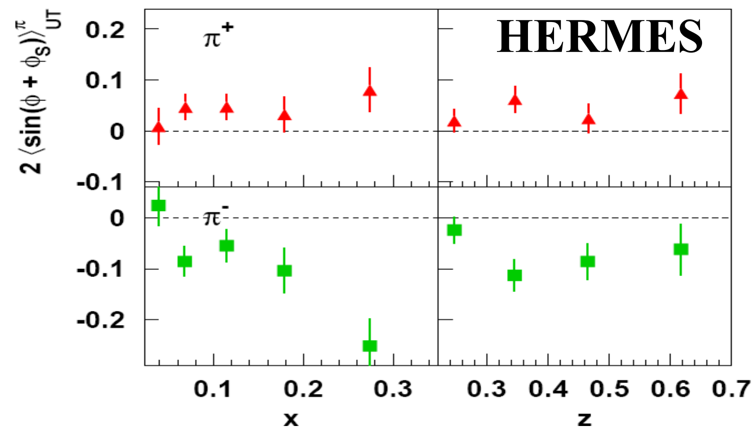
$\phi_{C}=\phi_h-\phi_S$, (fragmenting quark)

Collins fragmentation (Artru)

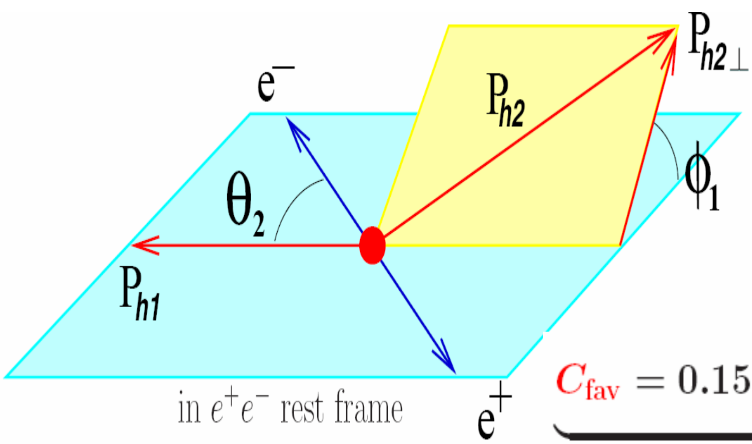




- L/R SSA generated in fragmentation
- Unfavored SSA with opposite sign
- No effect in target fragmenation

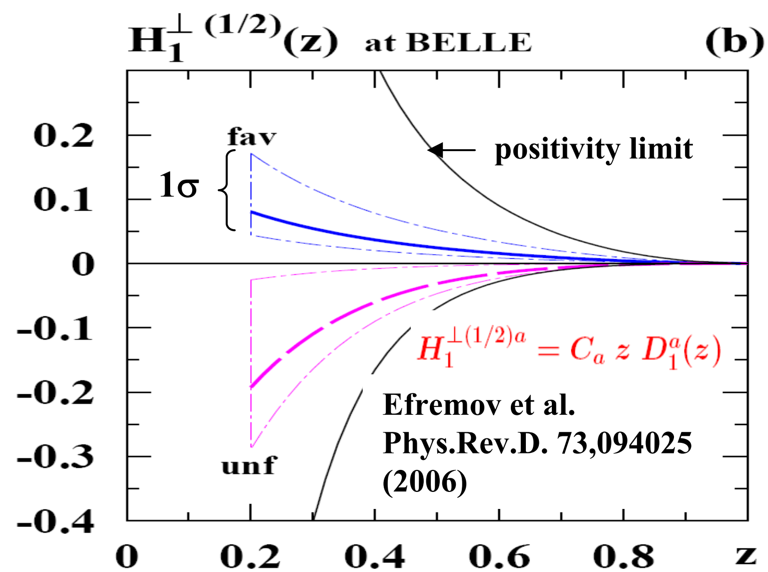


BELLE: Asymmetries in $e^+e^-\rightarrow h_1h_2X$ ($H^{\perp}_1$ $\bar{H}^{\perp}_1$)

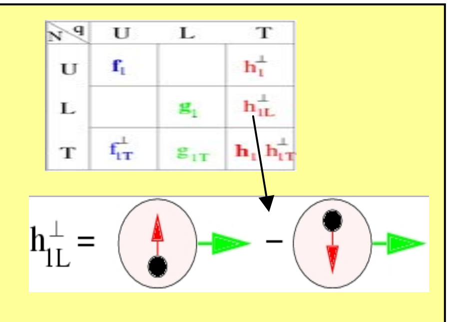


$$C_{\rm fav}=0.15,\quad C_{\rm unf}=-0.45$$

sign preferred by HERMES

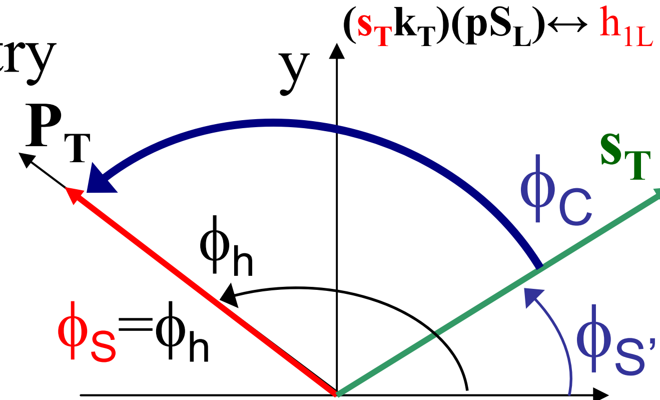


Collins fragmentation: Longitudinally polarized target

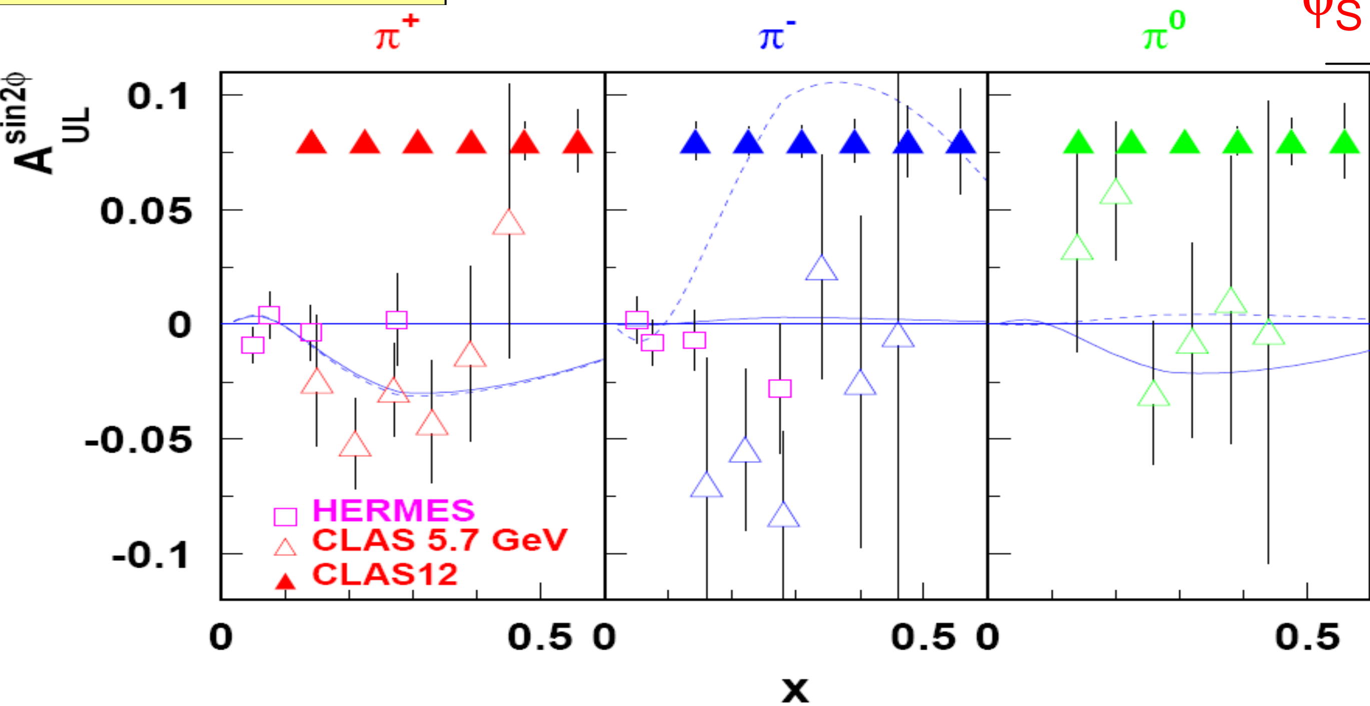


Kotzinian-Mulders Asymmetry

$\sigma_{UL}^{KM} \sim h_{1L}^{\perp} H_1^{\perp} \sin 2\phi_h$



$\sin(\phi_C) = \sin(2\phi_h)$



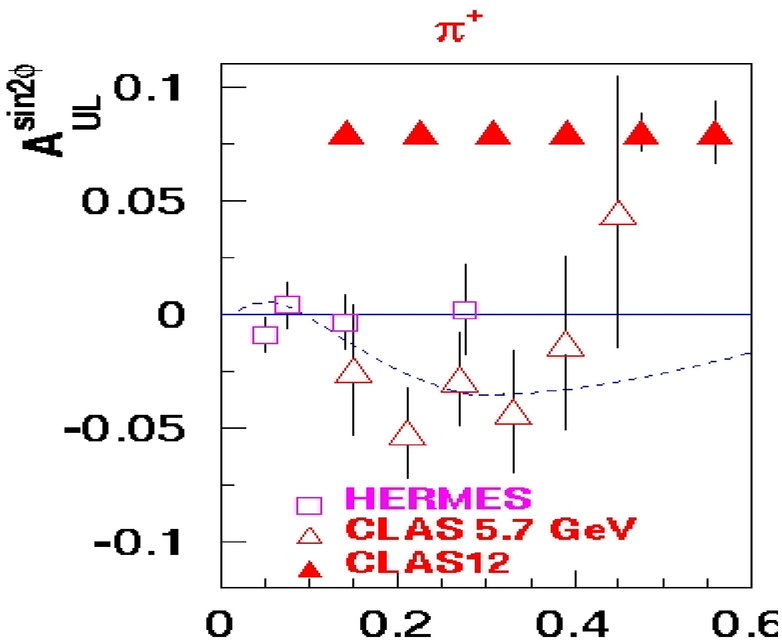
curves, χQSM
from Efremov et al

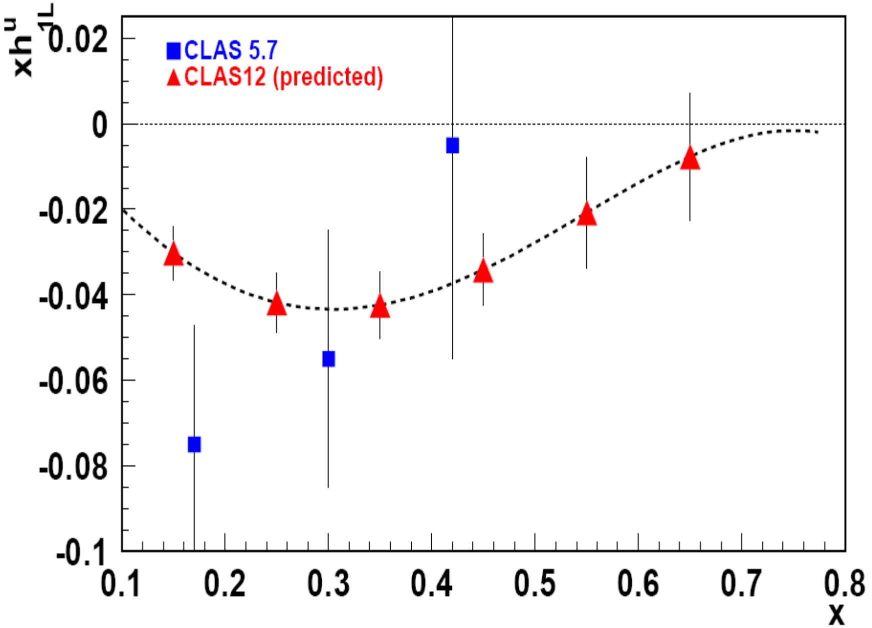
$H_1^{\perp u \to \pi^+} \approx -H_1^{\perp u \to \pi^-}$

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

CLAS12: Mulders TMD projections

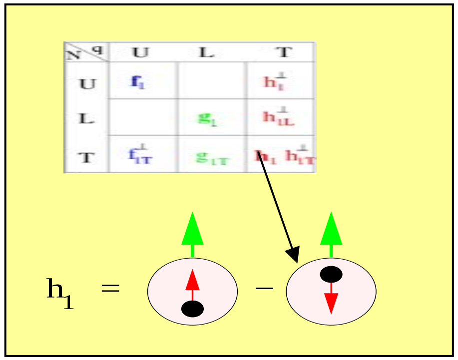
$$\sigma_{UL}^{KM} \sim (1-y) h_{1L}^{\perp} H_1^{\perp}$$



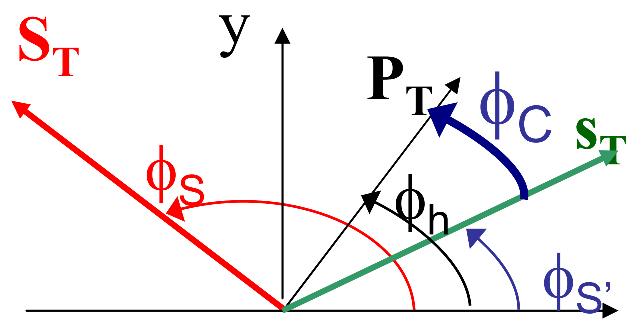


Simultaneous measurement of, exclusive ρ,ρ+,ω with a longitudinally polarized target important to control the background.

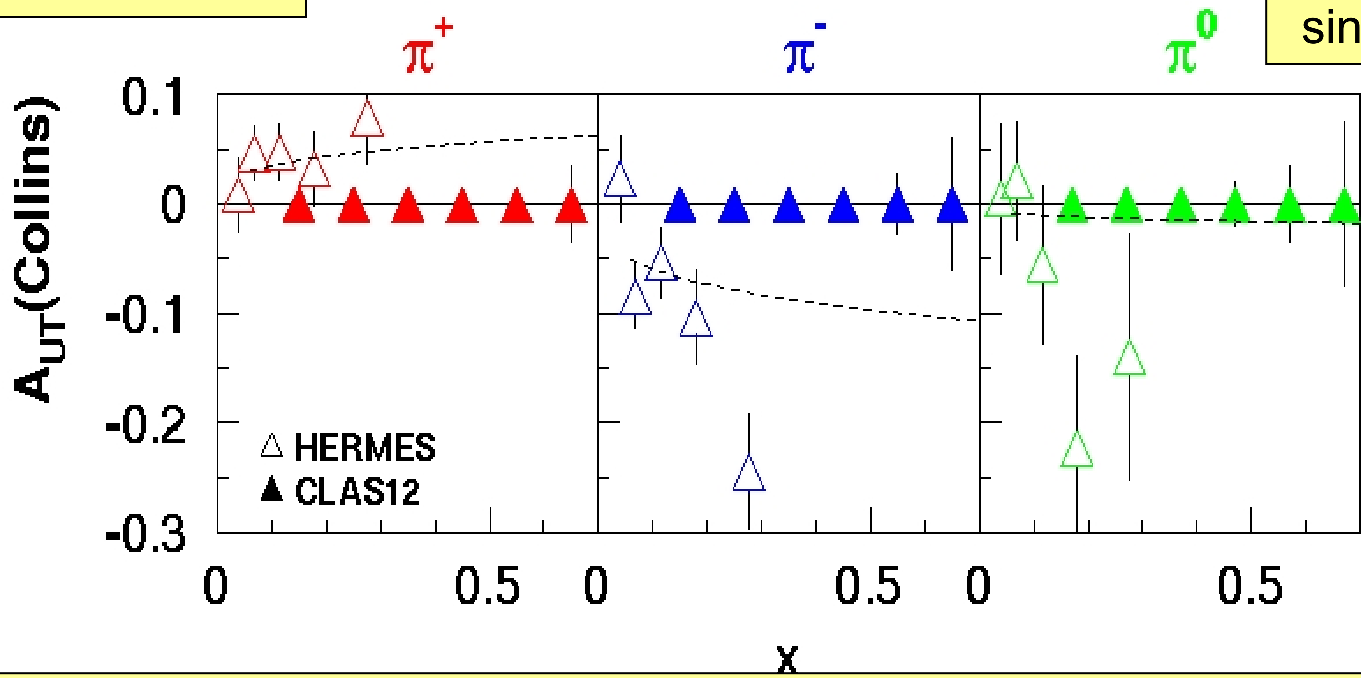
Collins fragmentation: Transverse target



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



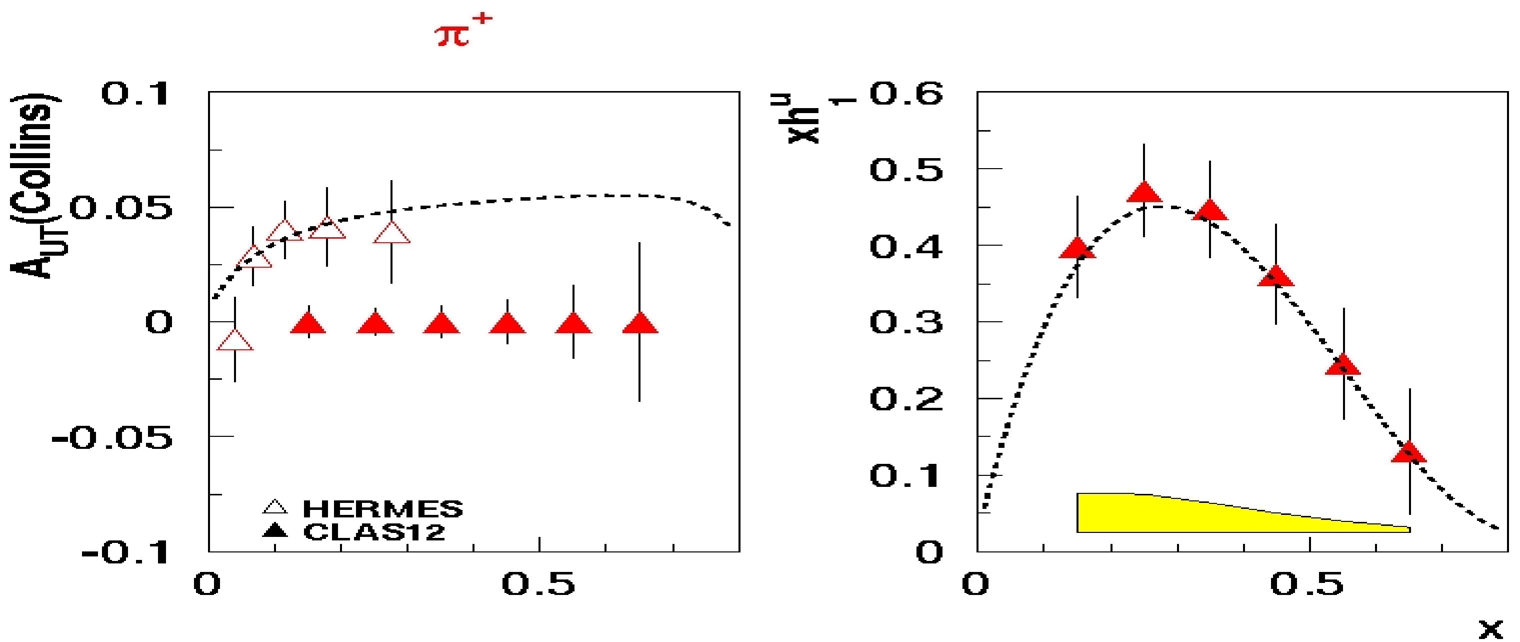
$\sin(\phi_C)=\sin(\phi_h+\phi_S)$



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

CLAS12: Transversity projections

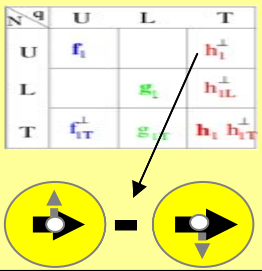
$$A_{UT}^{Collins} \sim (1-y)\, h_1 H_1^{\perp}$$



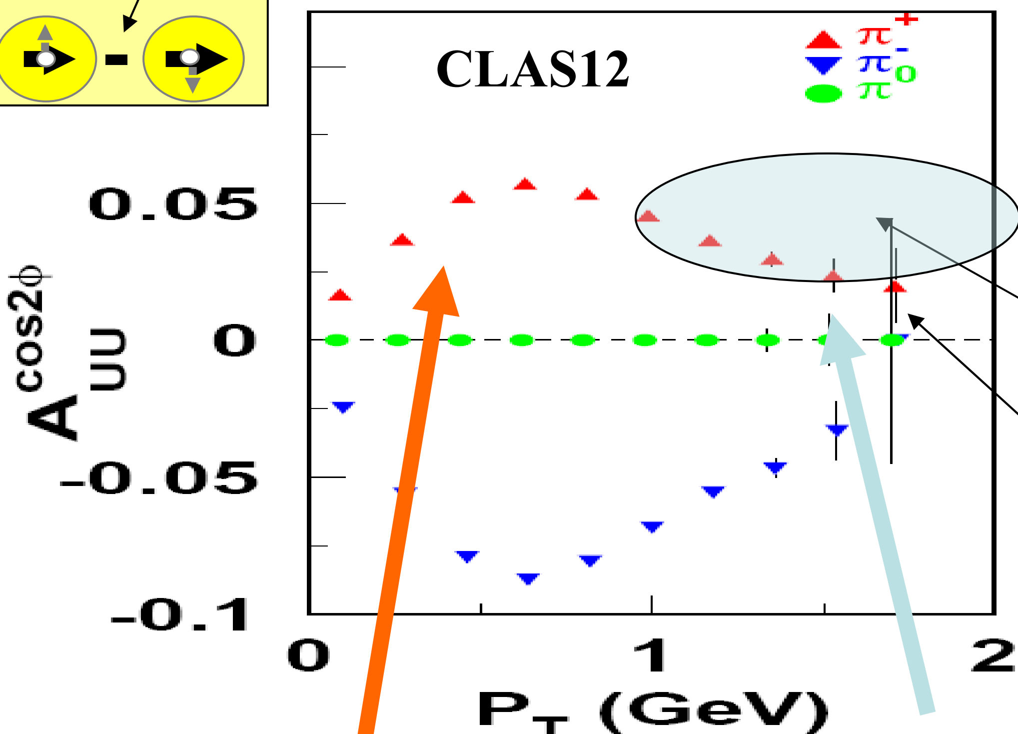
Simultaneous measurement of, exclusive $\rho,\rho+,\omega$ with a transversely polarized target

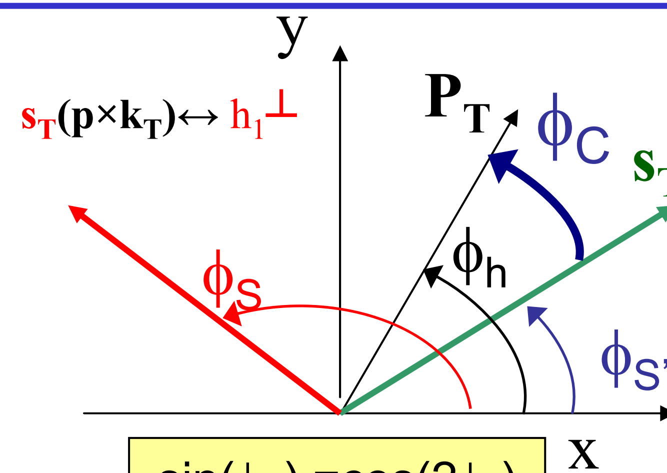
Collins function required to extract transversity from transverse target SSA measurements

Collins asymmetry & Boer-Mulders Effect



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





$\sin(\phi_C) = \cos(2\phi_h)$

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

quark-scalar diquark model

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

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

Non-perturbative TMD

Perturbative region

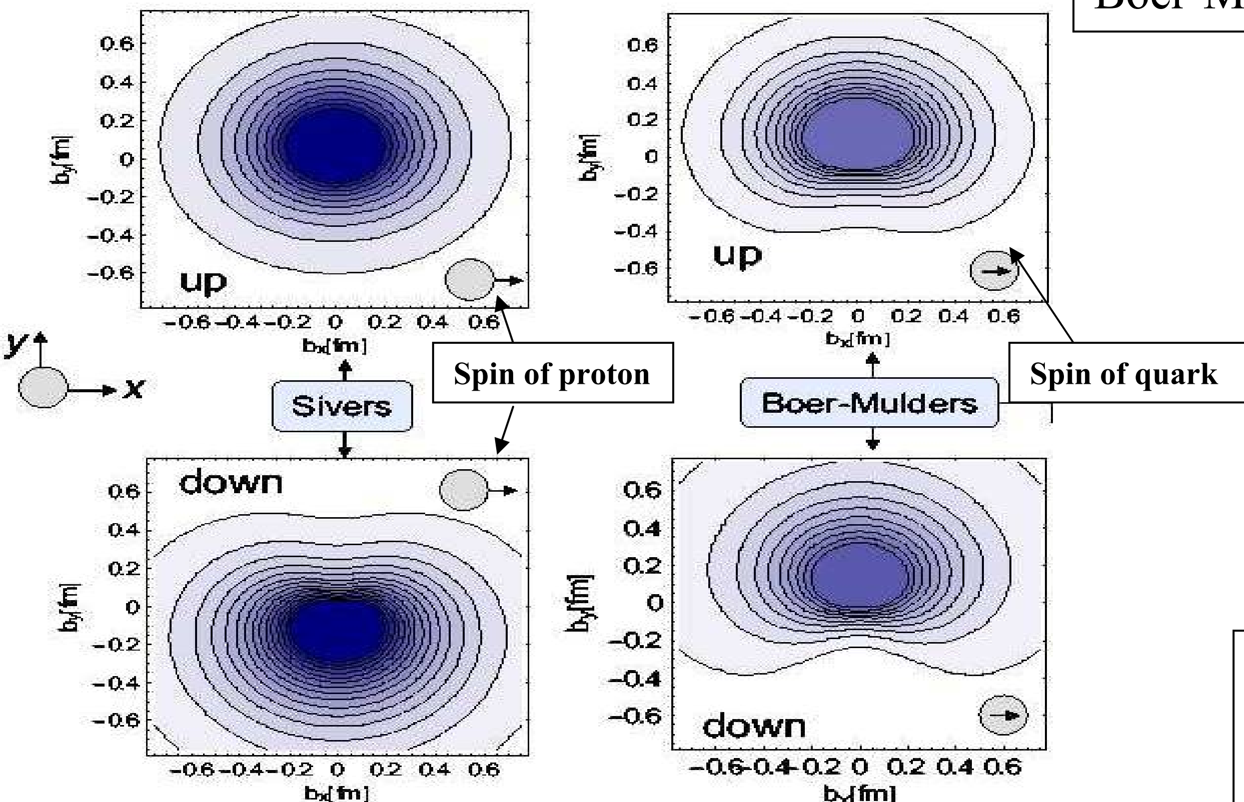
- •BM cos2ϕ moment: the only leading twist azimuthal moment for unpolarized target
- •**P_T**-dependence of BM asymmetry allows studies of transition from non-perturbative to perturbative description (Unified theory by Ji et al).
- •More info will be available from SIDIS (HERMES,COMPASS,ZEUS,EIC) and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

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)



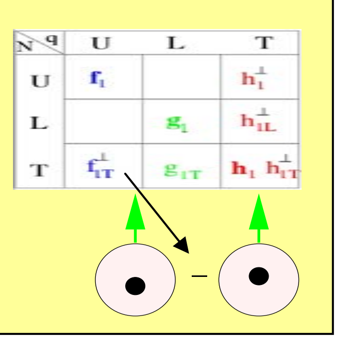
Burkardt relation

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

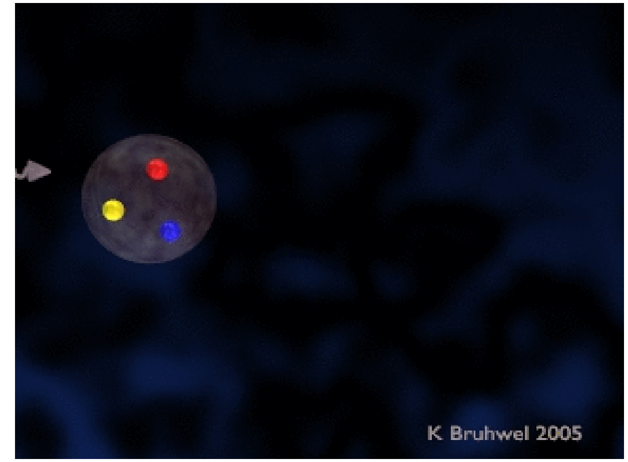
GPDs

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

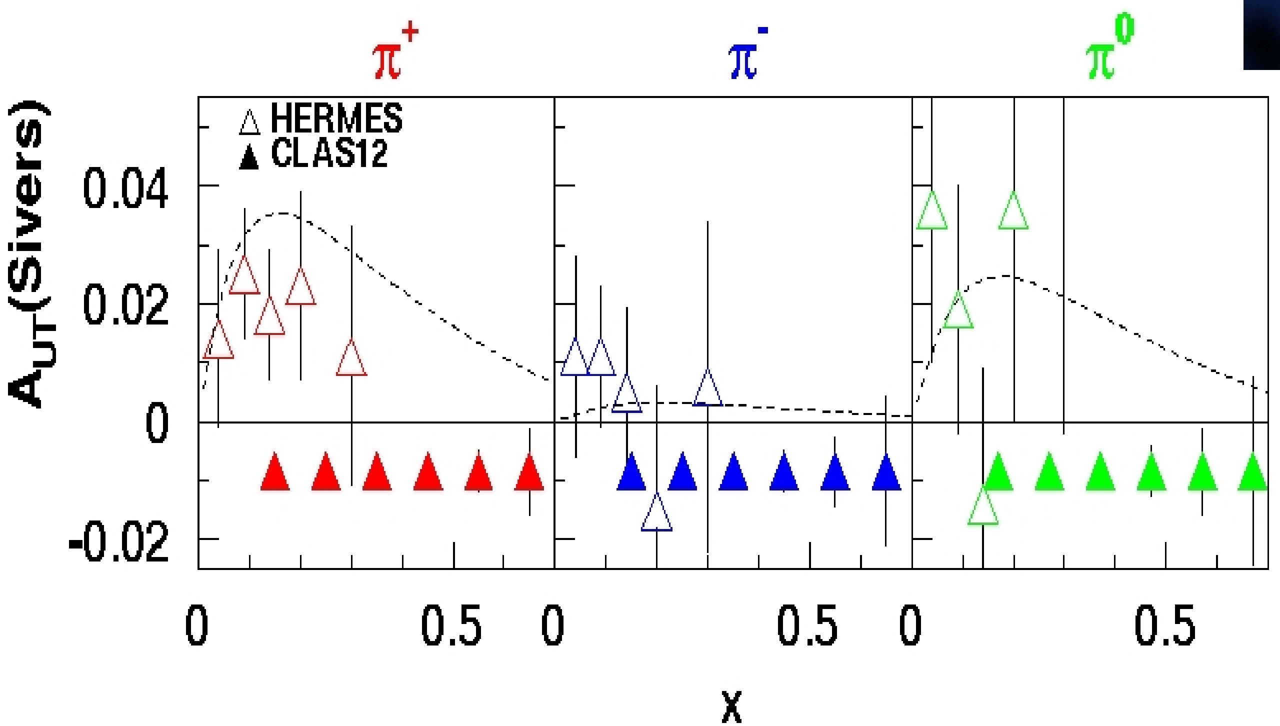
Both Lattice and GPD model calculations confirm large BM function!



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**

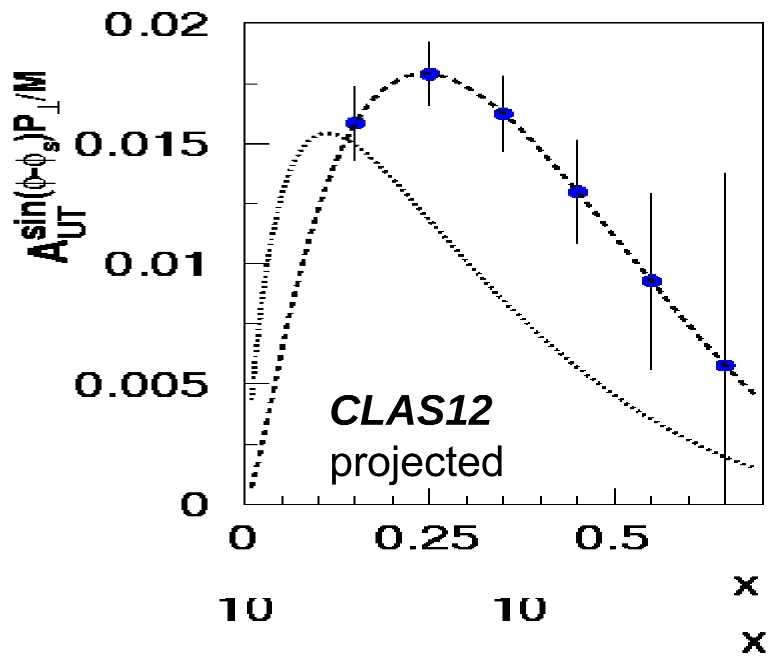
Requires: non-trivial phase from the FSI + interference between different helicity states

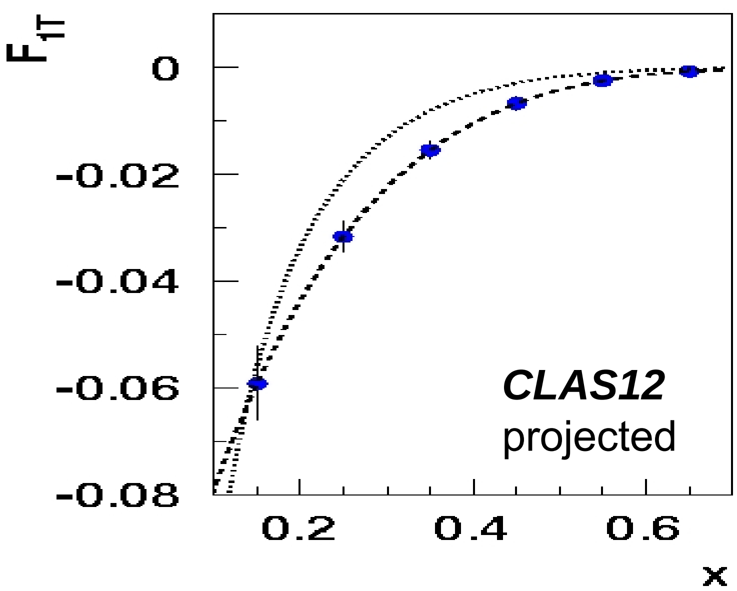
CLAS12: Sivers effect projections

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

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

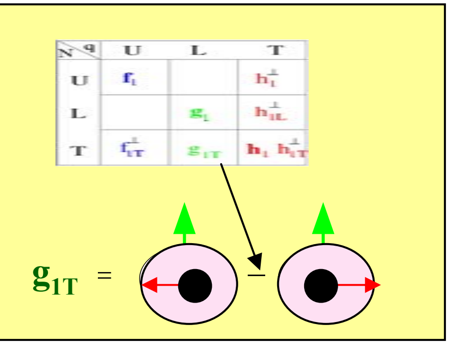
Efremov et al
(large x_B behavior of f_{1T} from GPD E)





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

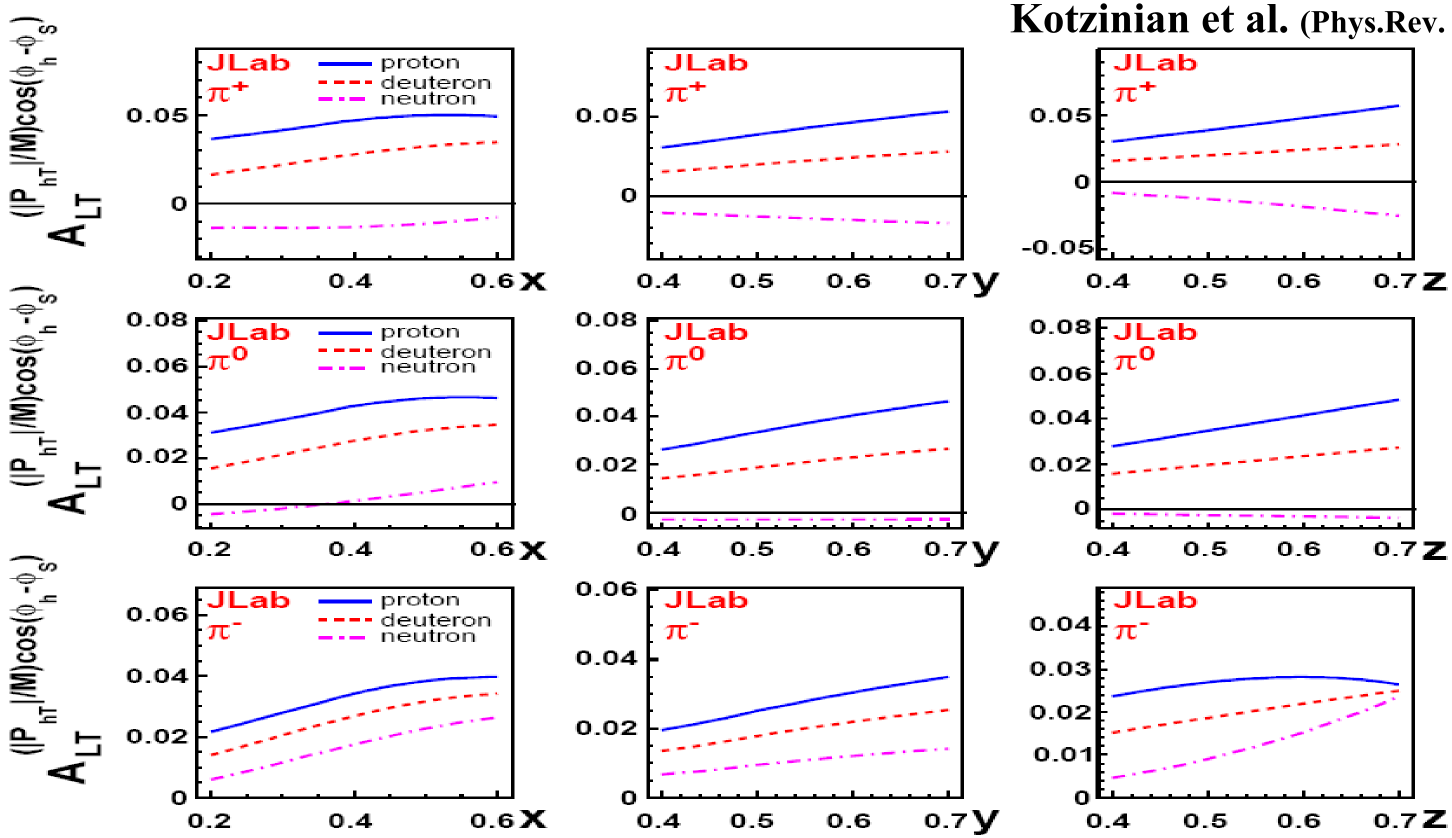
A_{UT} (π^0) on proton and neutron will allow flavor decomposition w/o info on FF.



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)

Higher Twist SSAs

Target sinϕ SSA (Bacchetta et al. 0405154)

Discussed as main sources of SSA due to the Collins fragmentation

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

In jet SIDIS only contributions ~ D_1 survive

The same unknown fragmentation function

Beam sinϕ SSA

$$A_{LU}^{\sin\phi} \approx \frac{2y\sqrt{1-y}}{(1-y+y^2)f_1 D_1}\frac{zMM_h}{Q}\left[\frac{M}{M_h}xg^{\perp(1)}D_1 + xeH_1^{\perp(1)} - \frac{M_h}{M}f_1\frac{G^{\perp(1)}}{z} - h_1^{\perp(1)}\frac{E}{z}\right]$$

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

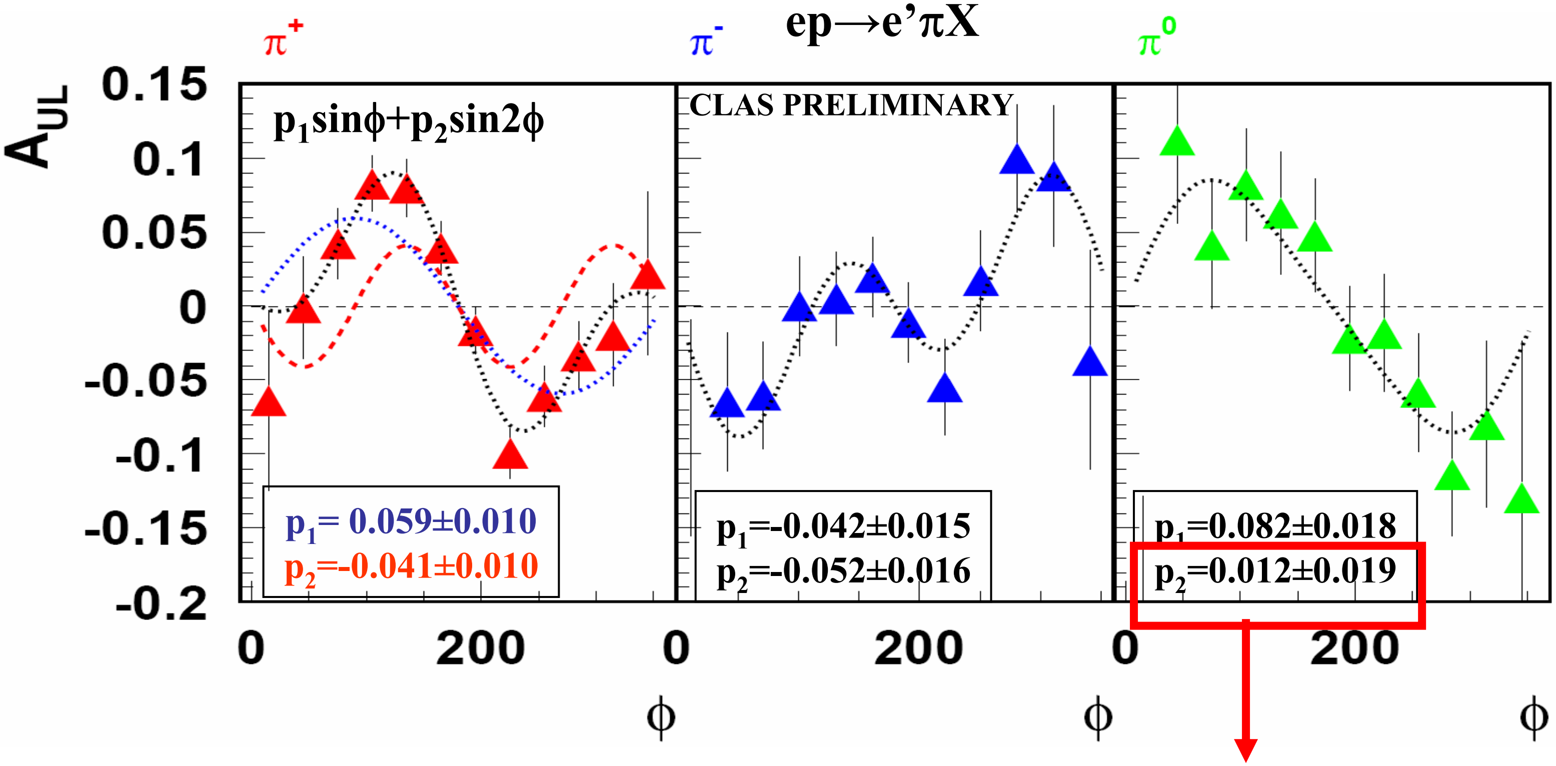
Target SSA measurements at CLAS

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

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

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

ep→e'πX



$W^2>4$ GeV^2
$Q^2>1.1$ GeV^2
$y<0.85$

$0.4<z<0.7$
$M_X>1.4$ GeV

$P_T<1$ GeV
$0.12<x<0.48$

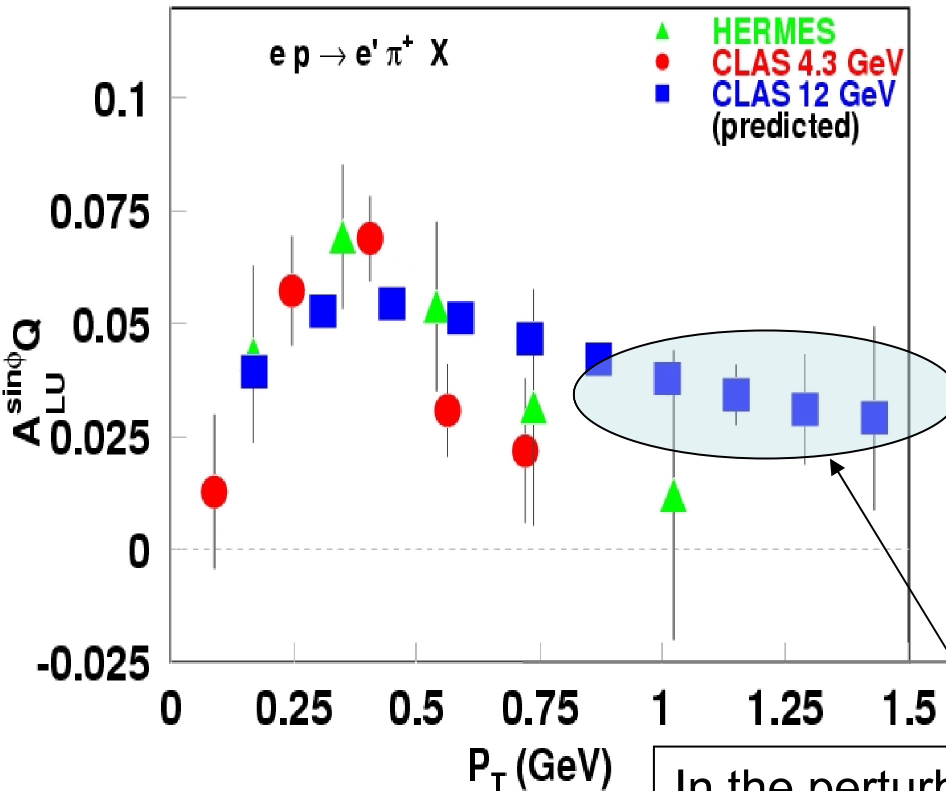
No indication of Collins effect for π^0 (x20 more data expected)

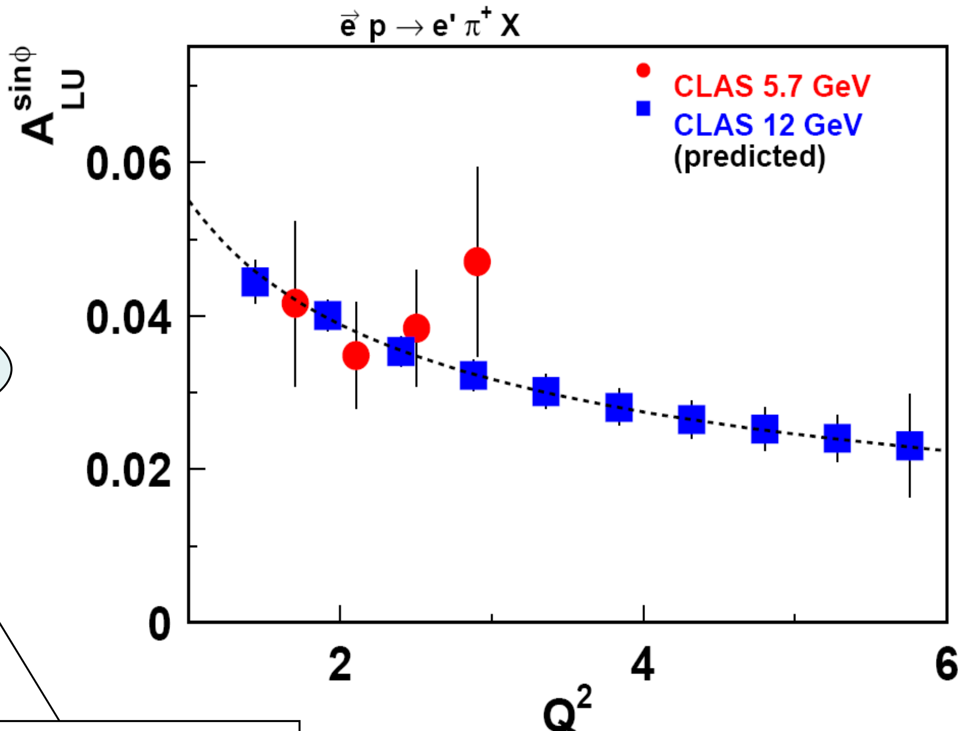
Beam SSA: CLAS @ 12 GeV

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**



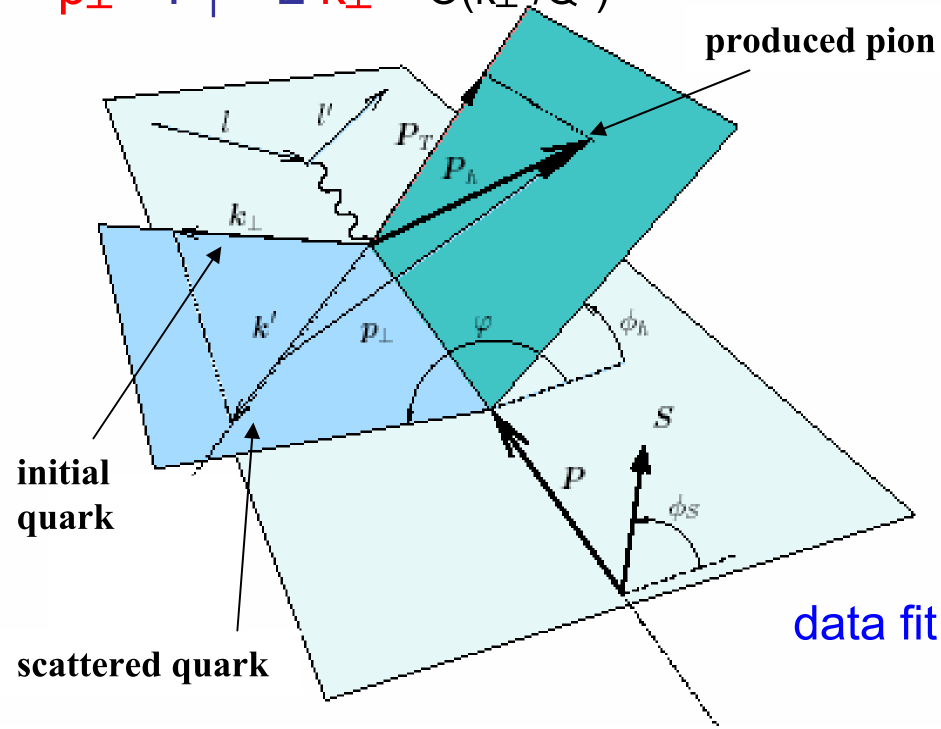


In the perturbative limit
$1/P_T$ behavior expected

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

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)

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

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

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

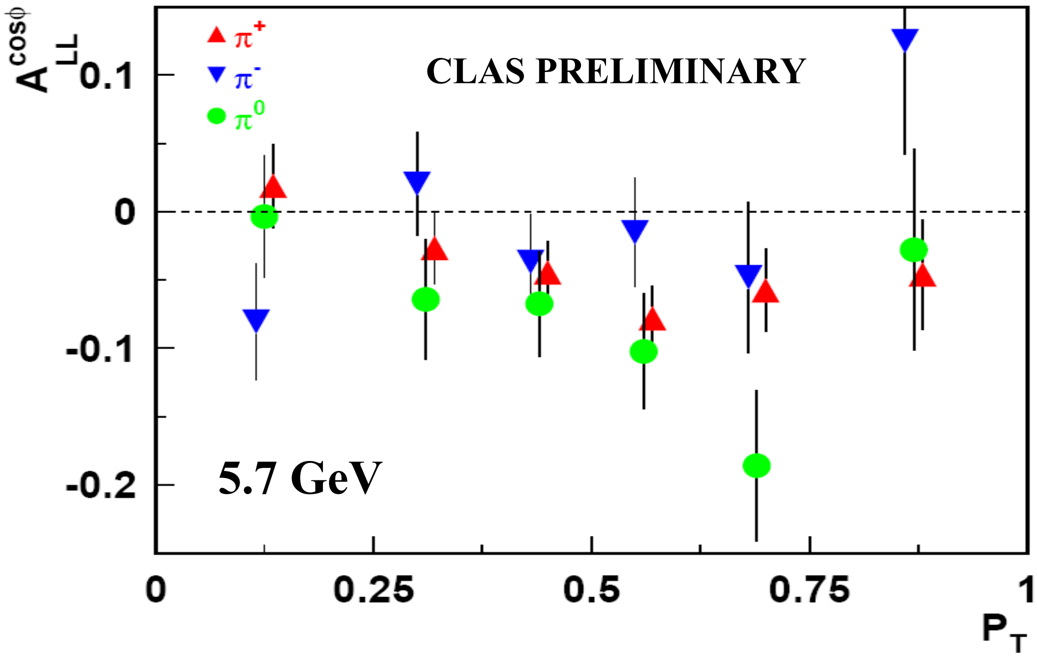
data fit on Cahn effect $\rightarrow \mu_0^2 = 0.25\,\mathrm{GeV}^2, \mu_D^2 = 0.2\,\mathrm{GeV}^2$

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

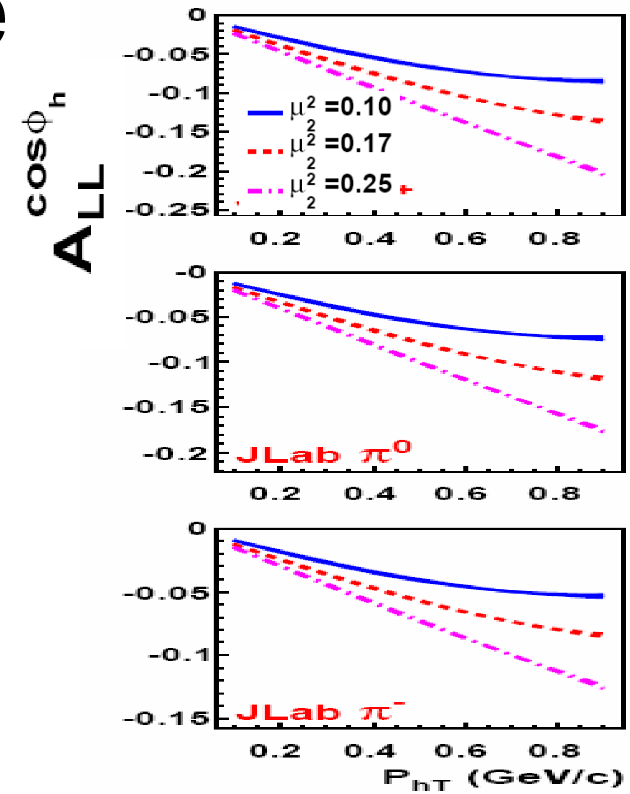
$$\sigma \sim \left[1 + (1-y)^2 - 4(2-y)\sqrt{1-y}\, \frac{z\mu_0^2 |\mathbf{P}_{hT}|}{Q(\mu_D^2 + \mu_0^2 z^2)} \cos\varphi_h\right] \frac{\exp\left(-\frac{\mathbf{P}_{hT}^2}{\mu_D^2 + \mu_0^2 z^2}\right)}{\mu_D^2 + \mu_0^2 z^2} \sum_q e_q^2\, f_1^q(x)\, D_q^h(z)$$

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

A_1-P_T-dependence



Anselmino et al. hep-ph/0608048



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

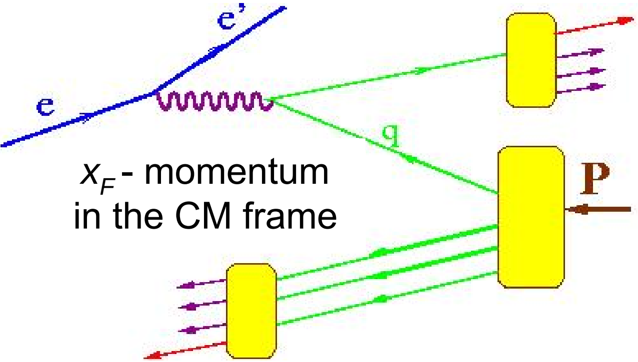
$$\Delta\sigma_{LL}^{\cos\phi_h} = -4\,\frac{\sqrt{1-y}}{xy}\,\frac{z\,\mu_2^2\,P_{hT}}{Q\,(\mu_D^2+z^2\mu_2^2)^2}\exp\left(-\frac{P_{hT}^2}{\mu_D^2+z^2\mu_2^2}\right)\sum_q e_q^2\, g_1^q(x)\, D_q^h(z)$$

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

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

Analysis of the polarized data, requires detailed knowledge of quark transverse momentum dependent distributions from unpolarized data and may provide additional info on difference in widths of k_T distributions

Cahn effect in the target fragmentation



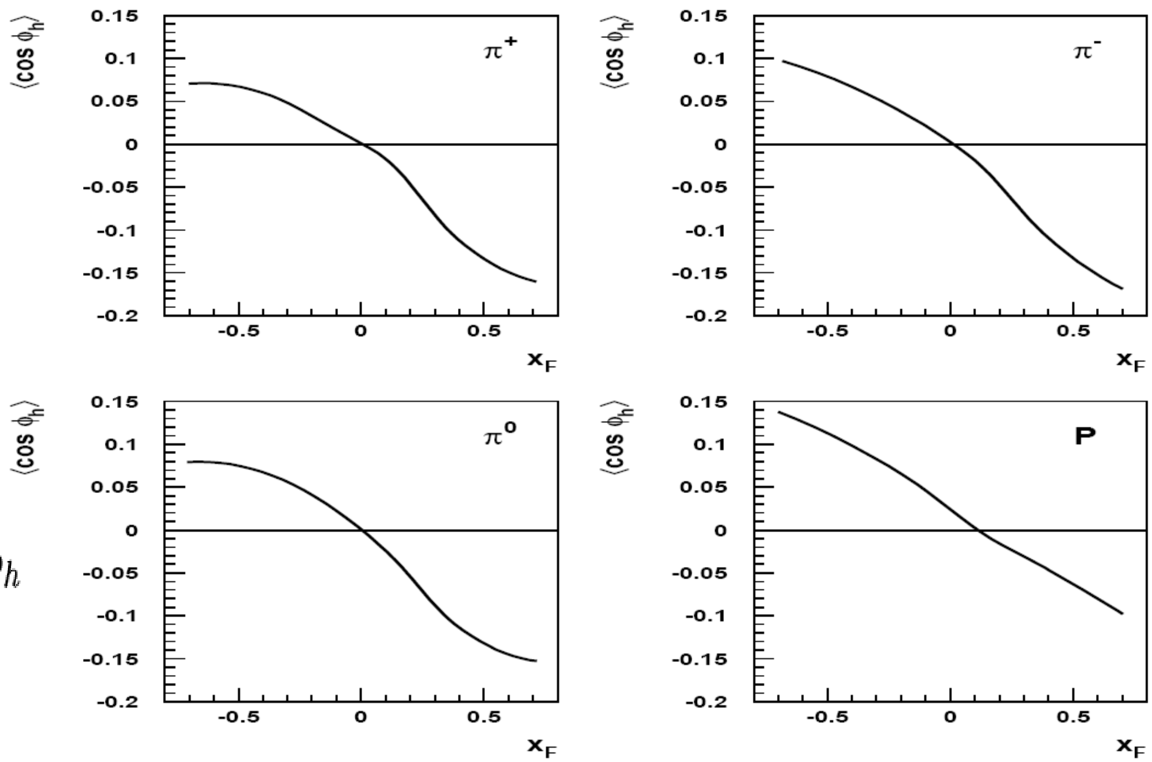
x_F - momentum in the CM frame

Transverse momentum of current quark is balanced by the target remnant

$$-4\,\frac{(2-y)\sqrt{1-y}\,\mu_0^2\,z_h\,|\vec{P}_T|}{\mu_H^2\,Q}\,\cos\phi_h$$

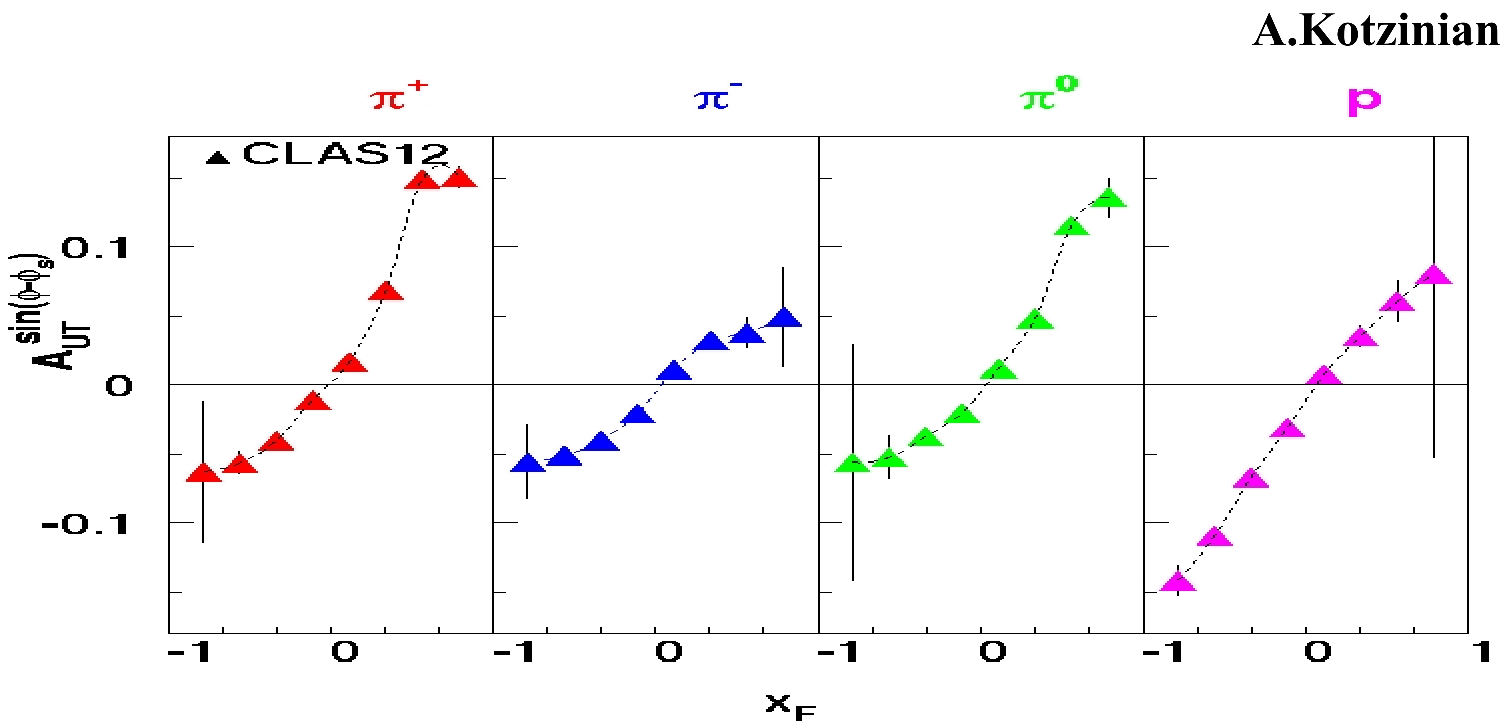
$$\mu_H^2 = \mu_D^2 + z_h^2\mu_0^2$$

A.Kotzinian (hep-ph/05103159)



High statistics of CLAS12 will allow studies of Q^2 dependence of the Cahn effect in current and target fragmentation region

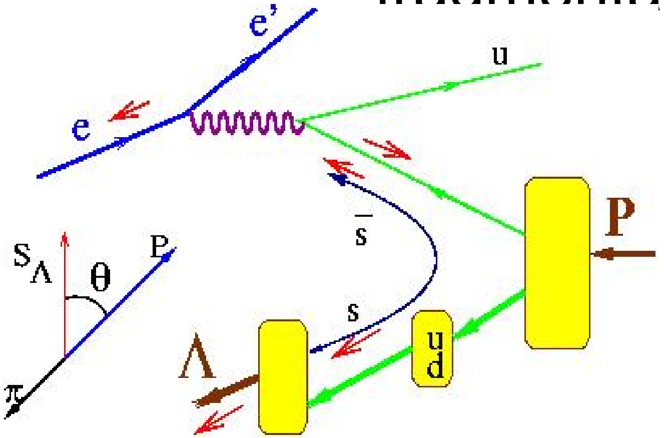
Sivers effect in the target fragmentation



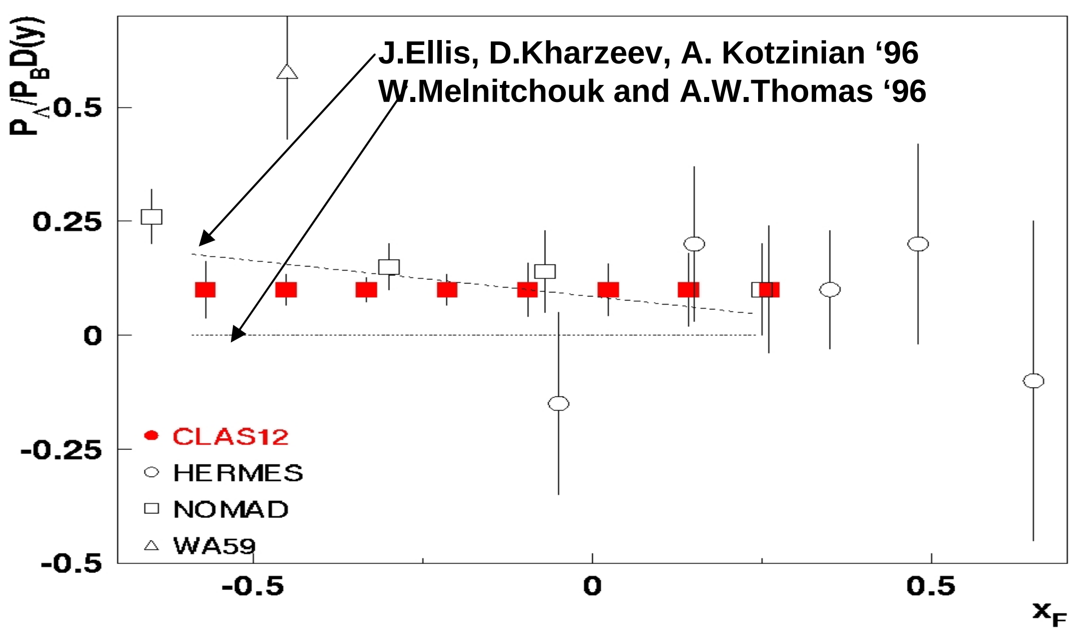
High statistics of CLAS12 will allow studies of kinematic dependences of the Sivers effect in target fragmentation region

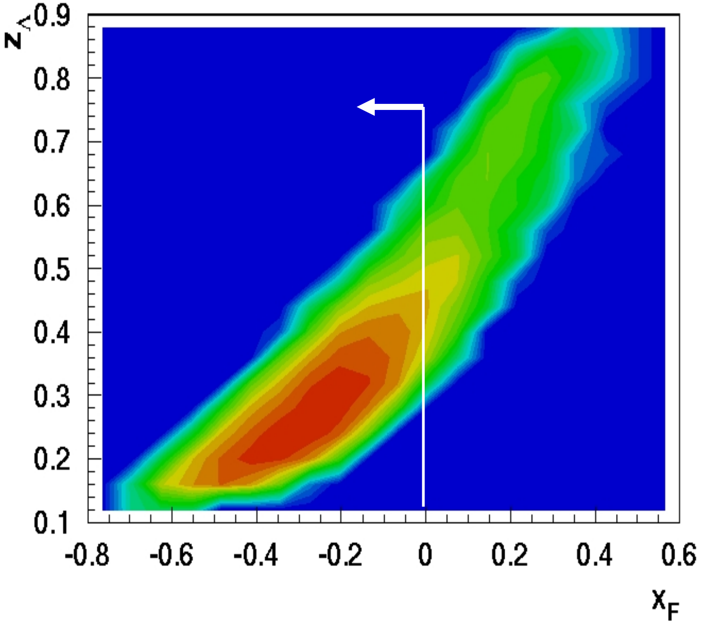
Λ polarization in the target fragmentation

A.Kotzinian,J.Ellis



Λ polarization in TFR provides information on contribution of strange sea to proton spin





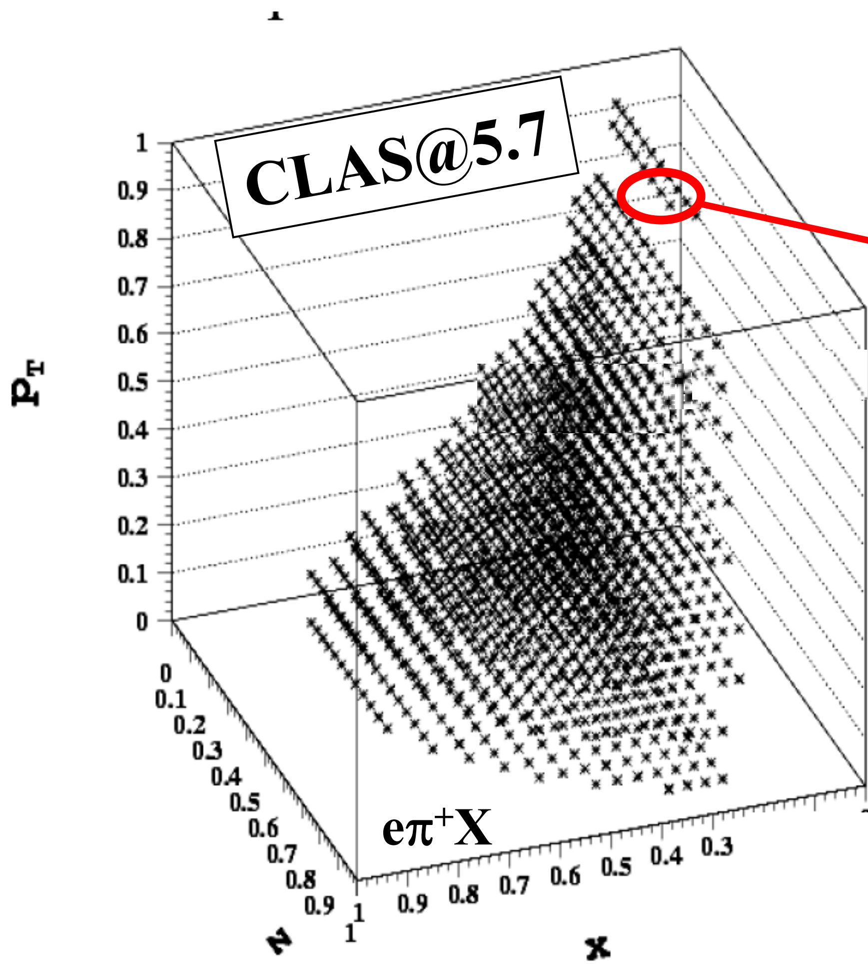
Wide kinematical coverage of CLAS12 allows studies of hadronization in the target fragmentation region

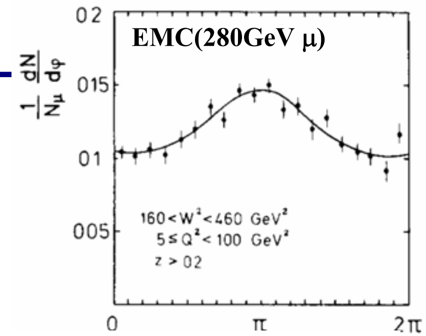
Summary

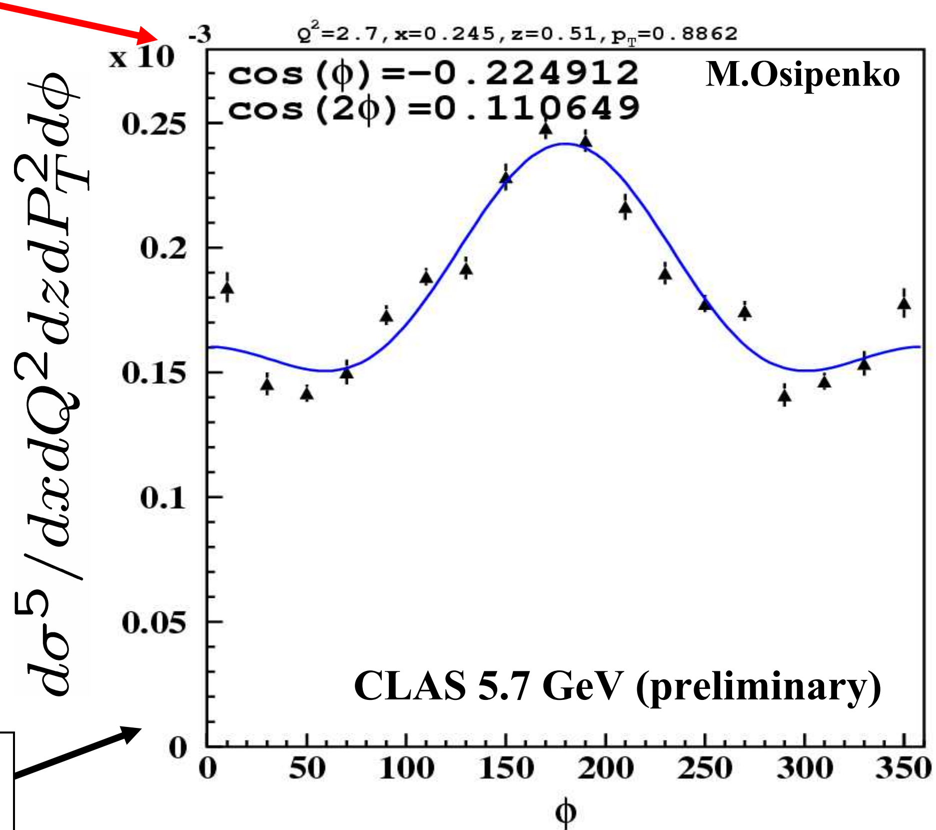
- Study of azimuthal moments in pion production in SIDIS provide important
  - Measurement of Collins asymmetry with unpolarized and polarized targets provide access to leading twist chirall-odd distribution functions (Boer-Mulders and transversity distributions)
  - Measurement of Sivers function in 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.
- Wide physics acceptance of CLAS12 would allow detailed studies of target fragmentation effects.

support slides…

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.

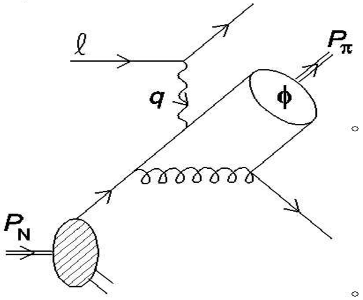
Azimuthal Asymmetries in SIDIS

- Intrinsic transverse momentum of partons (Cahn 1978)

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

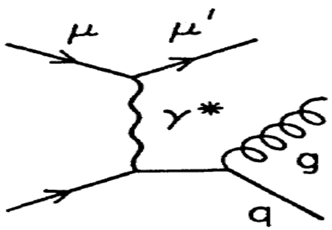
- Higher twists (Berger 1980, Brandenburg et al 1995)

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



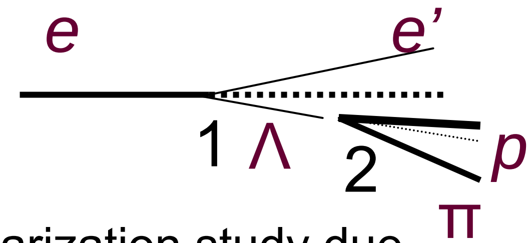
- Gluon bremsstrahlung (Georgi & Politzer, Mendez 1978) at z→1

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

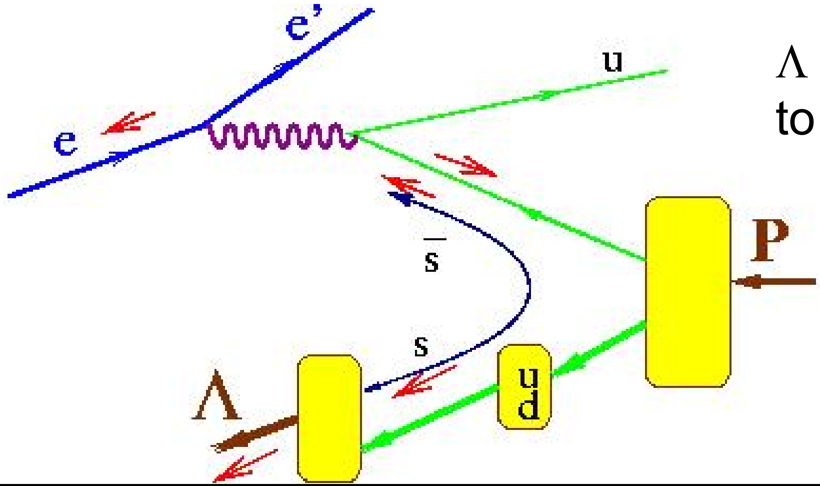


•Perturbative contribution negligible at low energies
•All known contributions to <cosϕ> and <cos2ϕ> are "flavor blind"

Λ in target fragmentation



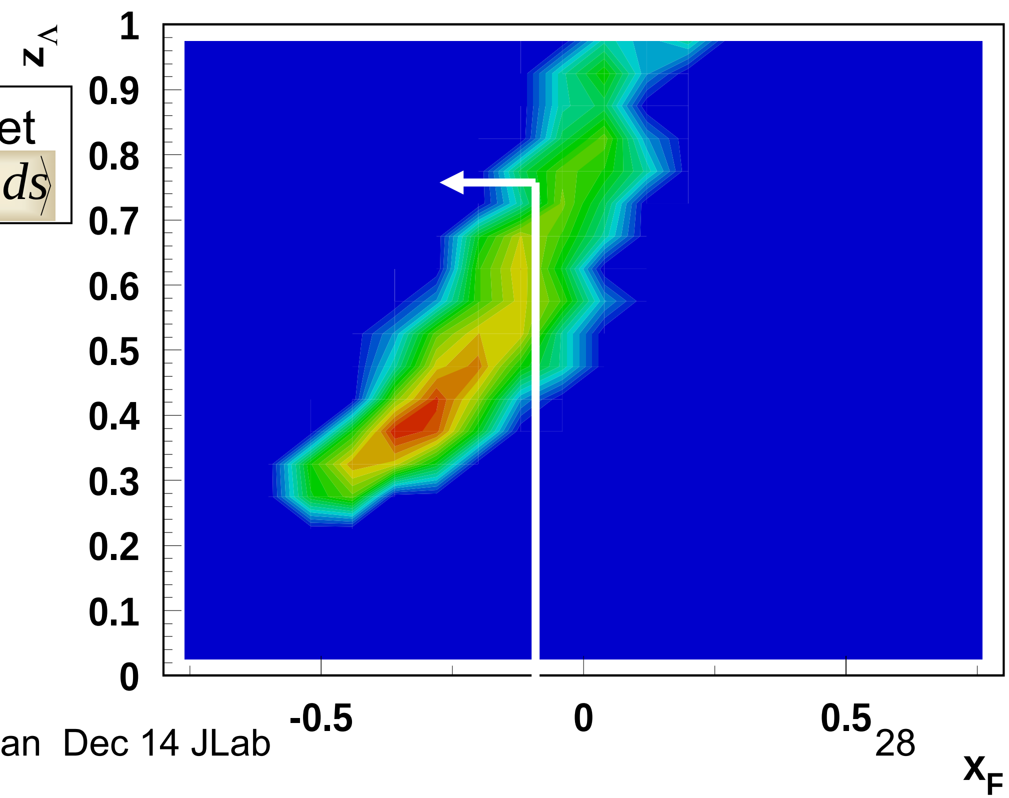
Λ – unique tool for polarization study due to self-analyzing parity violating decay



Accessing polarized PDFs with unpolarized target!

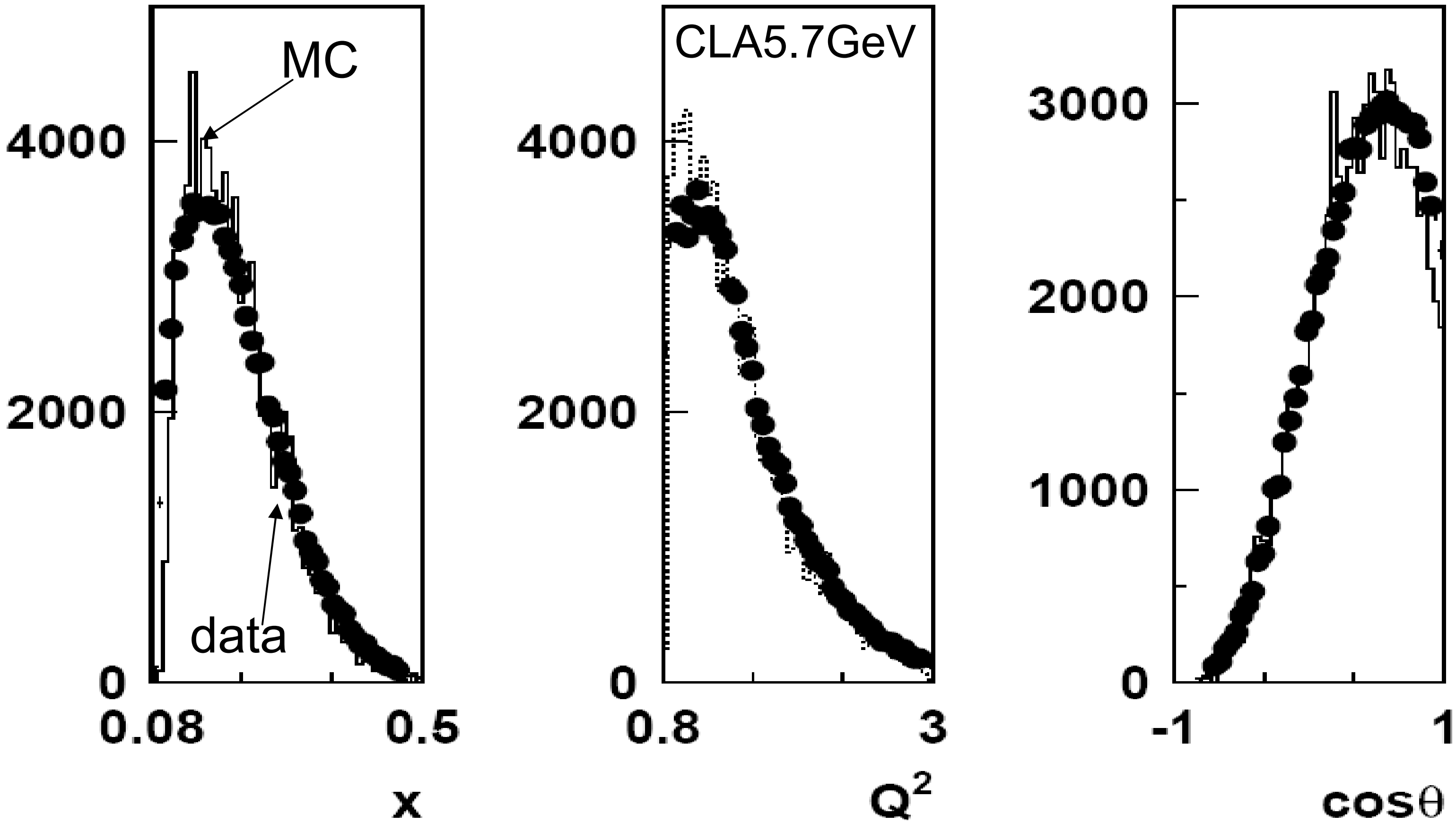
(ud)-diquark is a spin and isospin singlet
s-quark carries whole spin of Λ $|\Lambda\rangle = |uds\rangle$

Λs accessible in CLAS (even at large **z**) are mainly in the TFR region and can provide information on contribution of strange sea to proton spin



W.Melnitchouk and A.W.Thomas '96
J.Ellis, D.Kharzeev, A. Kotzinian '96

Λs in TFR: LUND MC vs CLAS data



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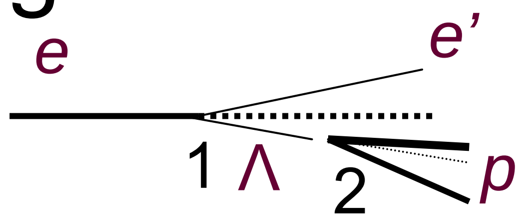
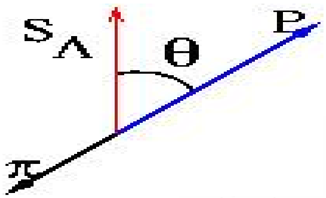
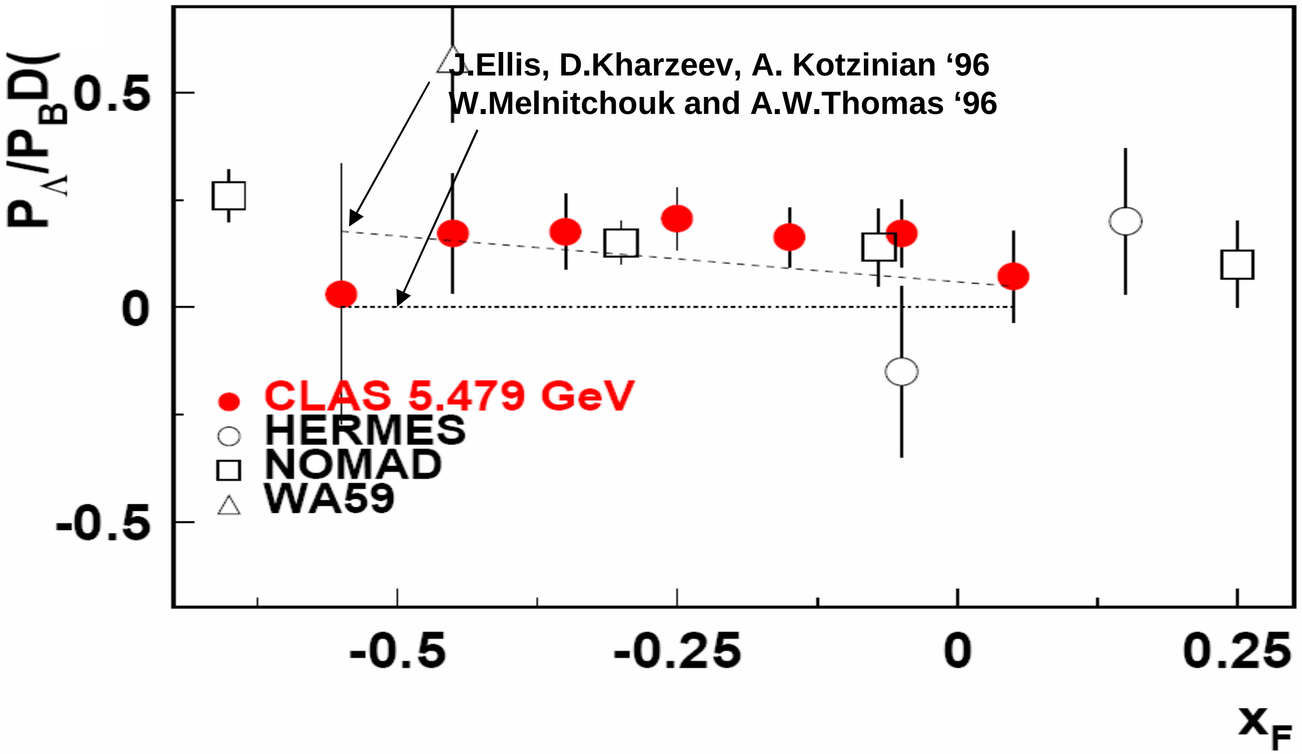
Shapes of distributions are consistent with LUND MC predictions.

Λ polarization in the target fragmentation

x_F - momentum
in the CM frame







Wide kinematical coverage of CLAS allows studies of hadronization in the target fragmentation region

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.

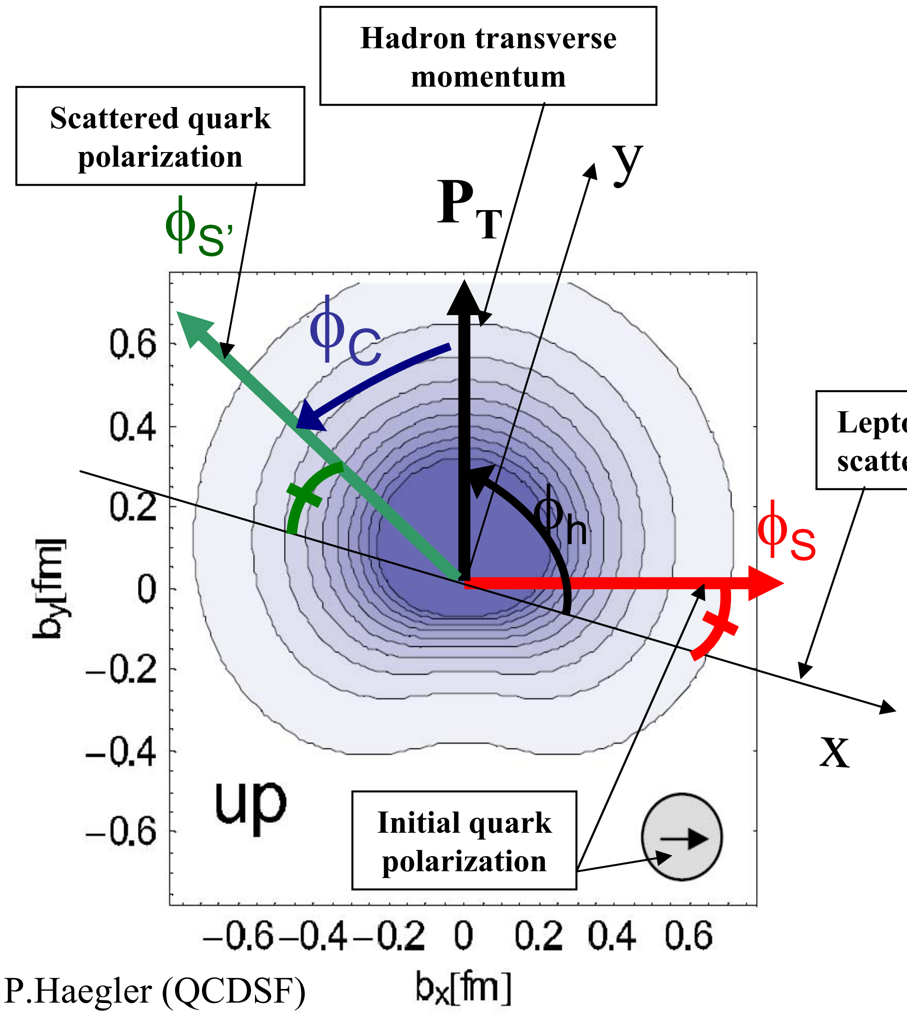
TMD PDFs k_T-even	TMD PDFs k_T-odd	FFs
f_1		D_1
	$h_1^\perp$	$H_1^\perp$
g_1		D_1
	$h_{1L}^\perp$	$H_1^\perp$
	f_{1T}	D_1
	g_{1T}	D_1
h_1		$H_1^\perp$
	$h_{1T}^\perp$	$H_1^\perp$
$\sim(1-x)^3$	$\sim(1-x)^4$	

Brodsky et al 2006

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

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

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

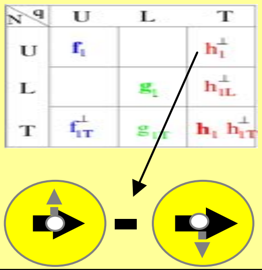
$$A_{UU} \propto h_1^\perp H_1^\perp \sin(\phi_h - \phi_{S'})$$

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

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

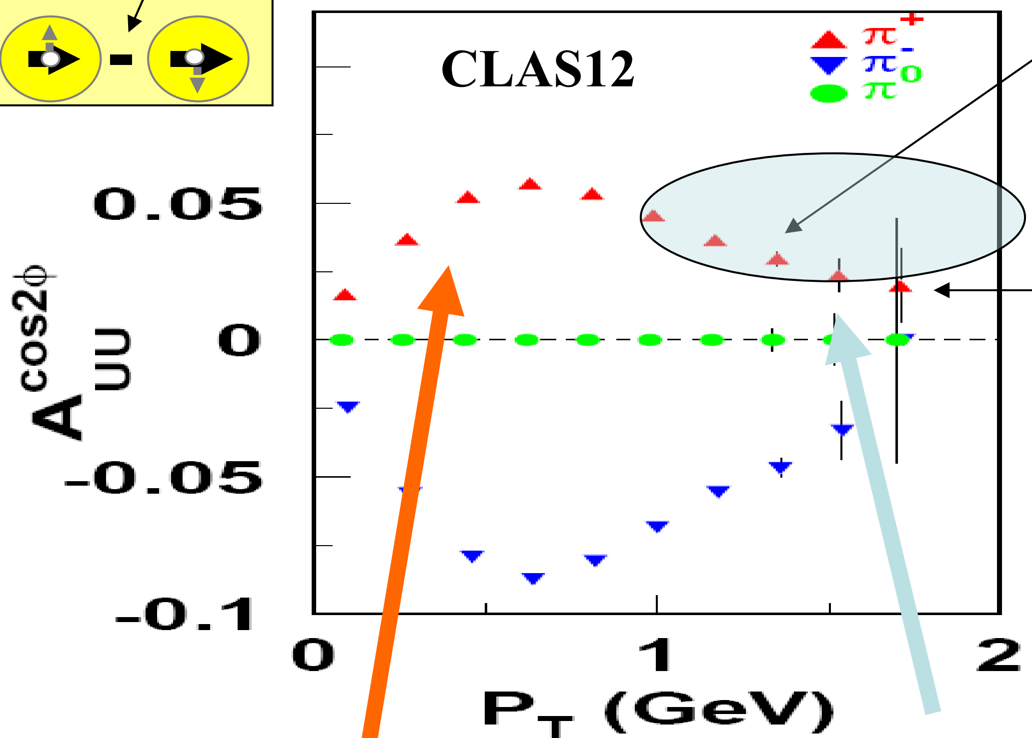
Sideways shift in distribution of transversely polarized quarks in the unpolarized proton may lead to Collins asymmetry for final state hadrons (**Burkardt,Diehl,Hagler**)

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 $10^{35}\text{sec}^{-1}\text{cm}^{-2}$)

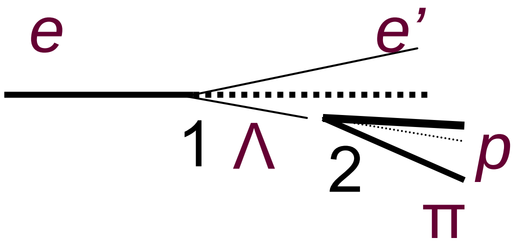
$$\Lambda_{QCD} \ll P_T \ll Q$$

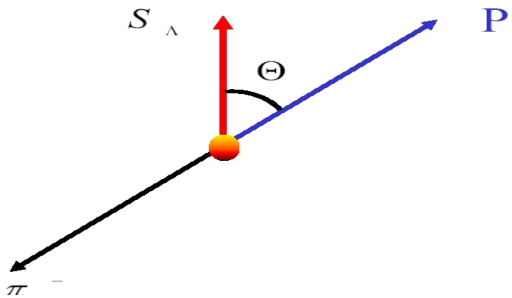
Non-perturbative TMD

Perturbative region

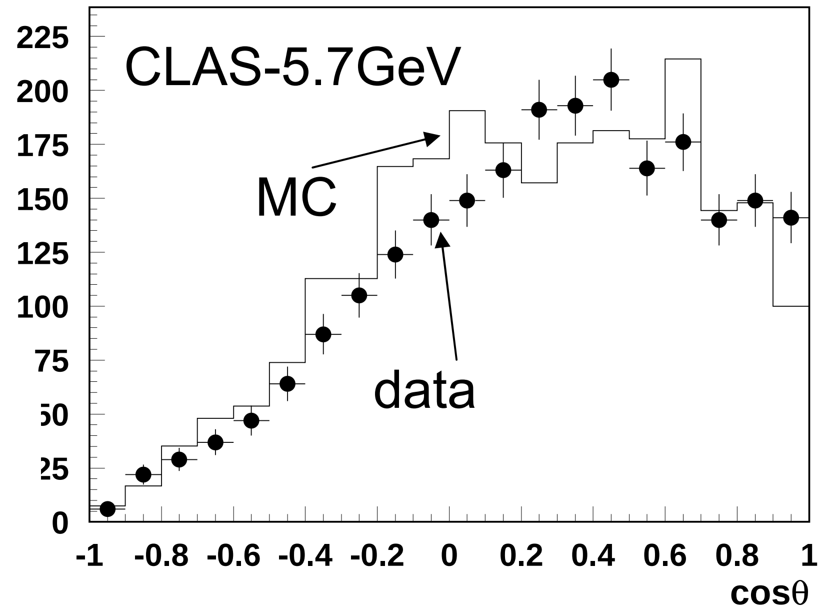
- BM cos2ϕ moment: the only leading twist azimuthal moment for unpolarized target
- **P_T**-dependence of BM asymmetry allows studies of transition from non-perturbative to perturbative description (Unified theory by Ji et al).
- More info will be available from SIDIS (HERMES,COMPASS,ZEUS) and DY (RHIC,GSI)

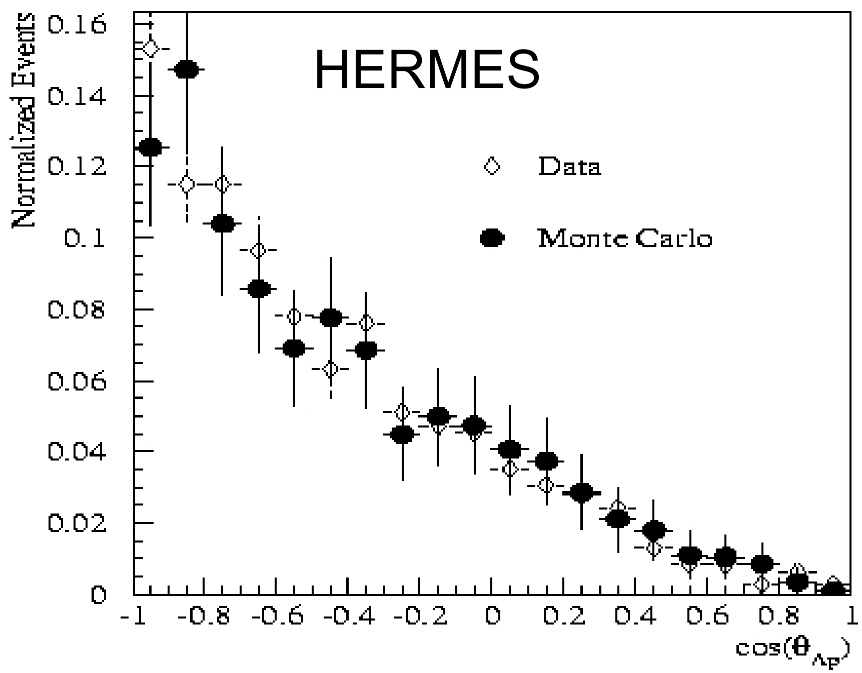
Λs in target fragmentation





$$\frac{d\sigma}{d\theta} = \sigma_0 A(\cos\theta)\left(1 + \alpha P_\Lambda \cos\theta\right)$$



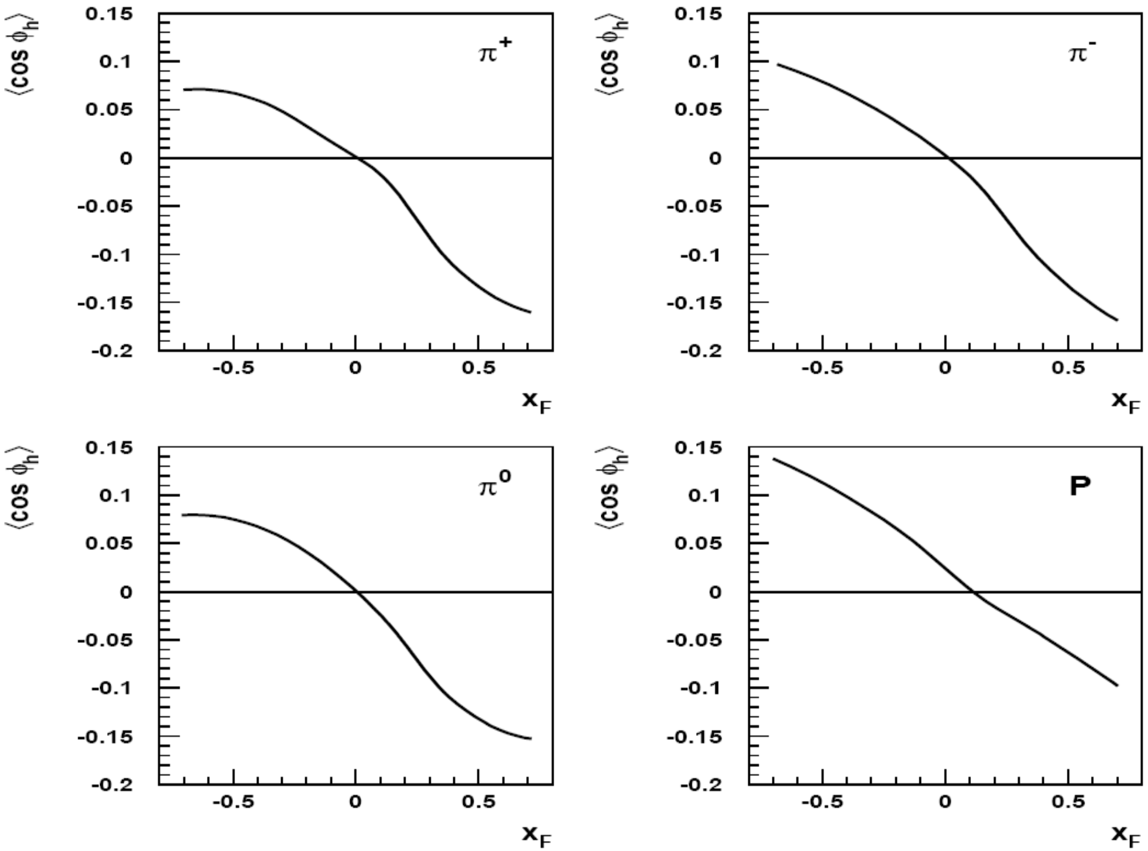


Presence of large cosθ from acceptance require:

1) Detailed MC simulation **OR**
2) Spin asymmetry measurement to cancel the acceptance contribution

Cahn effect in the target fragmentation

A.Kotzinian (hep-ph/05103159)



$$-4\,\frac{(2-y)\sqrt{1-y}\,\mu_0^2\,z_h\,|\vec{P_T}|}{\mu_H^2\,Q}\,\cos\phi_h$$

$$\mu_H^2 = \mu_D^2 + z_h^2\mu_0^2$$

Transverse momentum of current quark is balanced by the target remnant

High statistics of CLAS12 will allow studies of Q^2 dependence of the Cahn effect in current and target fragmentation region

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

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

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

→ gauge link contribution

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

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

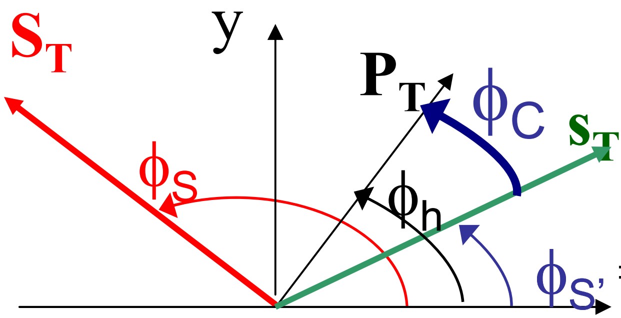
$$x f_L^{\perp d}(x) = \tfrac{4}{15}\left[A_{UL,n}^{\pi}\left(4d + u\right) - A_{UL,p}^{\pi}\left(u + d/4\right)\right]$$

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

Collins Effect: azimuthal modulation of the fragmentation function

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

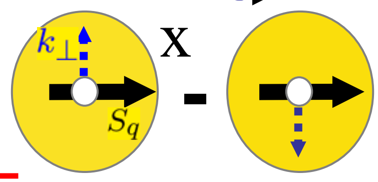
$s_T(q \times P_T) \leftrightarrow H_1^{\perp}$



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

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

→ $\sin(\phi_h + \phi_S)$

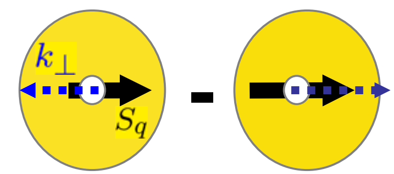


$F_{UU} \propto h_1^{\perp} H_1^{\perp}$

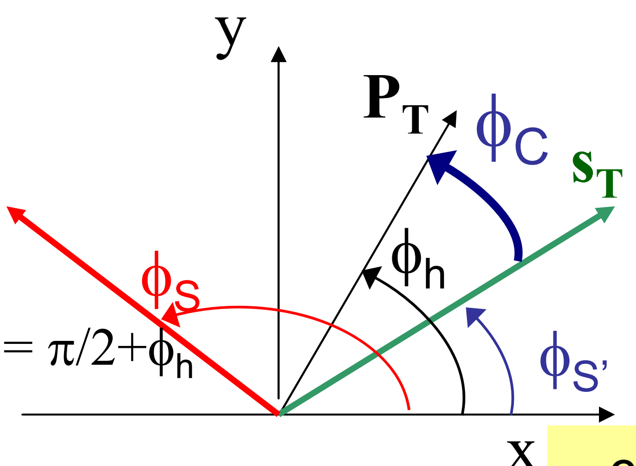
$s_T(p \times k_T) \leftrightarrow h_1^{\perp}$

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

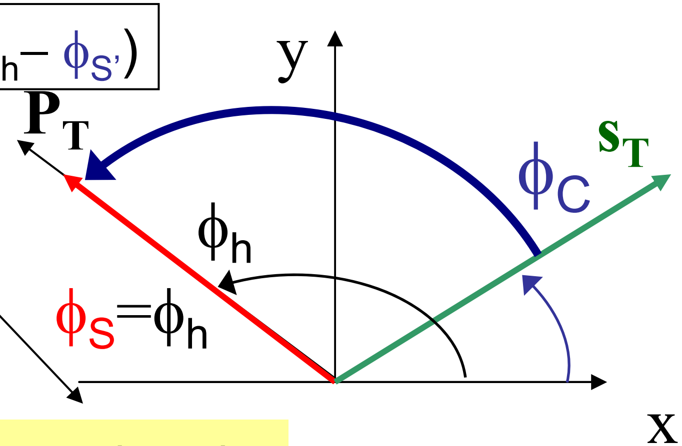
$(s_T k_T)(p S_L) \leftrightarrow h_{1L}^{\perp}$



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



$\phi_S = \pi/2 + \phi_h$



$\cos(2\phi_h)$

$\sin(2\phi_h)$

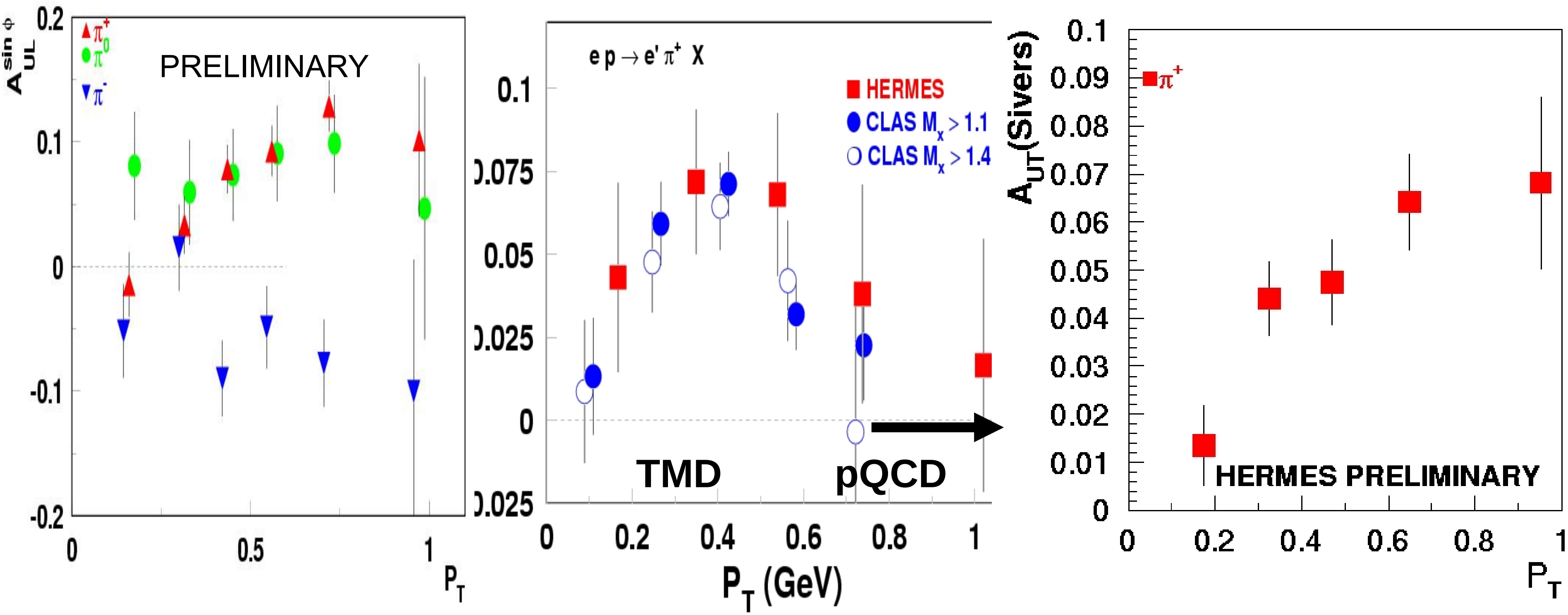
$\phi_{S'} = \pi - \phi_S = \pi/2 - \phi_h$

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

SSA: P_T-dependence of $\sin\phi$ moment

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

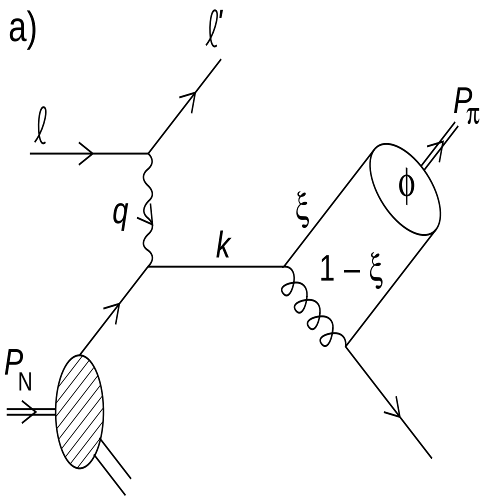
A_{UL} (CLAS @5.7 GeV) A_{LU} CLAS @4.3 GeV A_{UT} HERMES @27.5 GeV

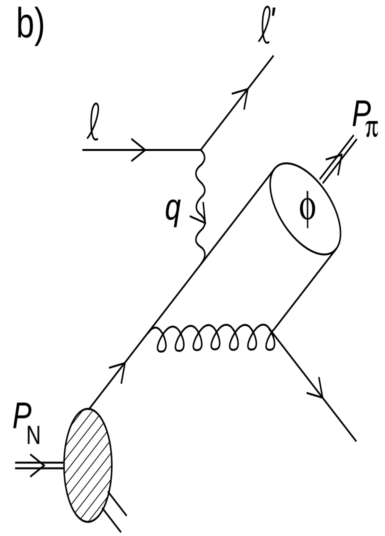


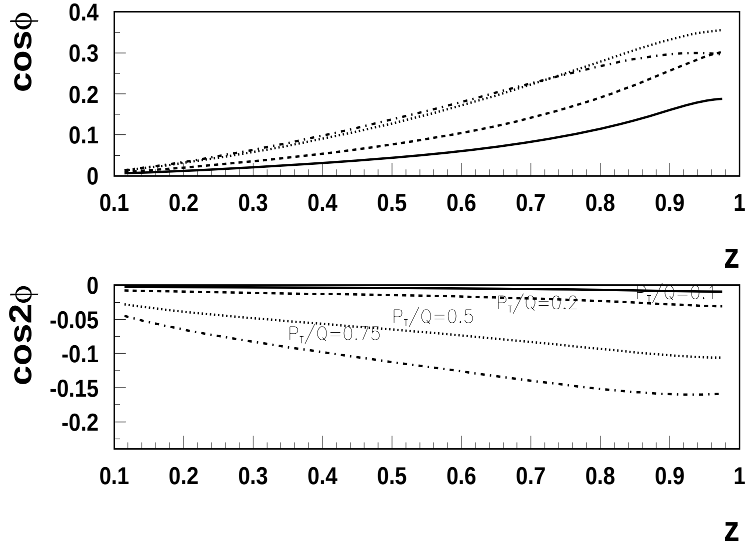
Beam and target SSA for π+ are consistent with increase with P_T
In the perturbative limit is expected to behave as $1/P_T$

Azimuthal Asymmetries in semi-exclusive limit

- Higher twists (Berger 1980, Brandenburg et al 1995)
  z→1 dominant contribution u+e- →e- π+ d

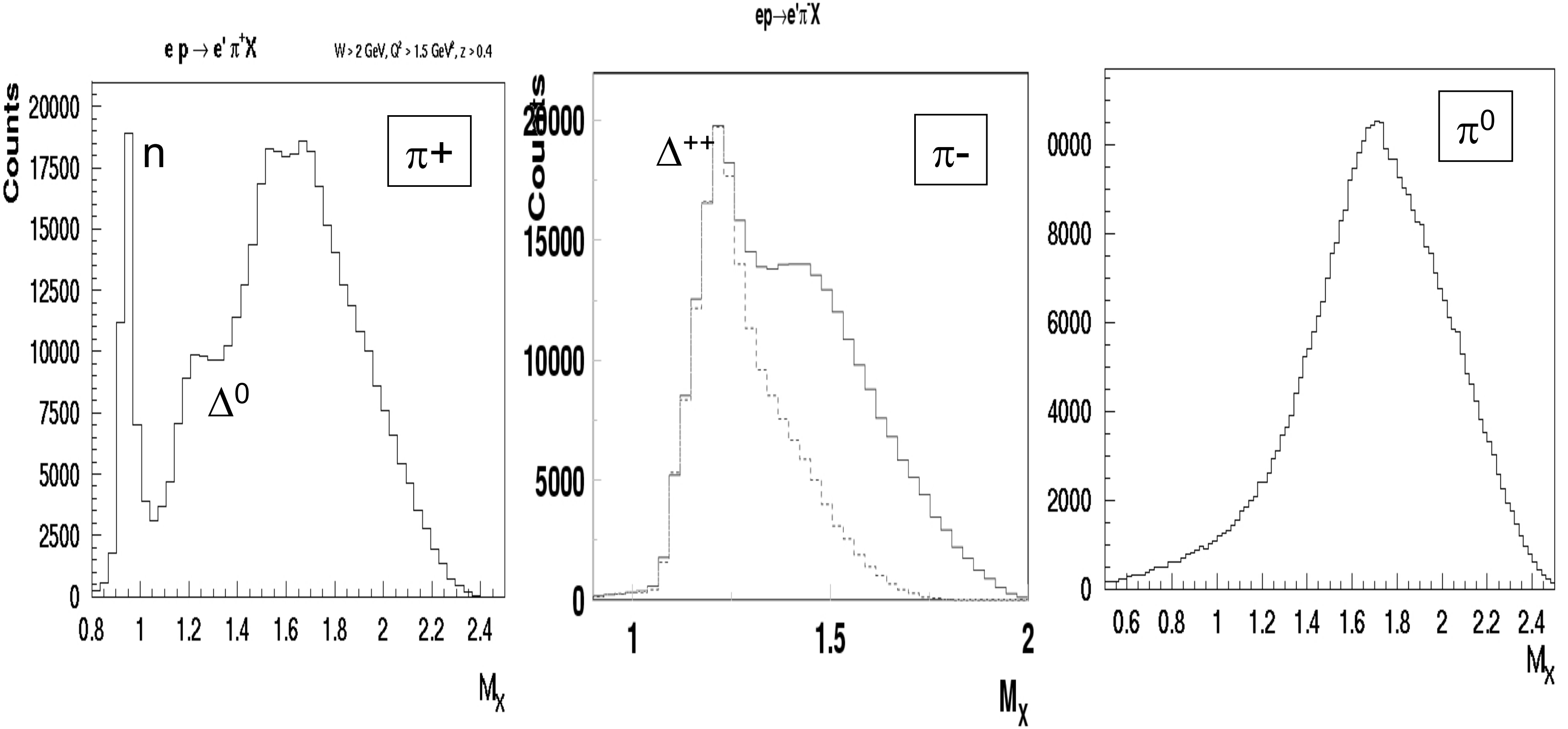






Dominant contribution to meson wave function is the perturbative one gluon exchange and approach is valid at factor ~3 lower Q^2 than in case of hard exclusive scattering (Afanasev & Carlson 1997)

Missing mass of pions in ep->e'πX

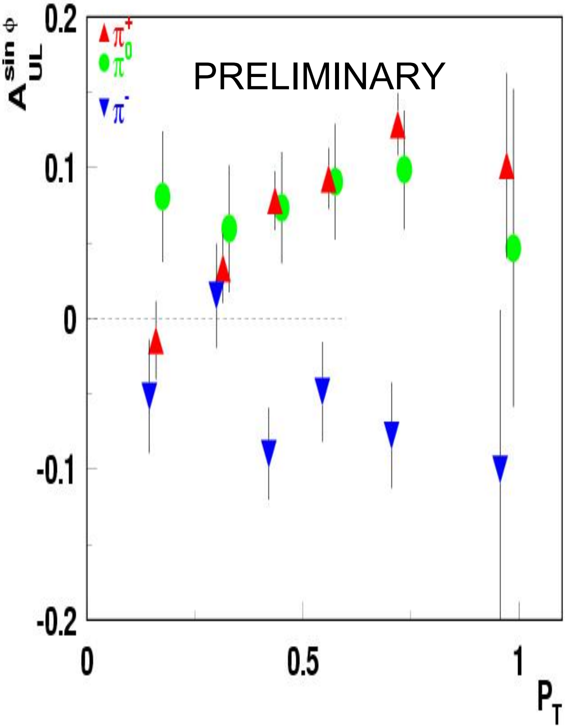


Large Delta(1232) contribution makes π- different (M_x>1.5 GeV applied)

SSA: P_T-dependence of sinϕ moment

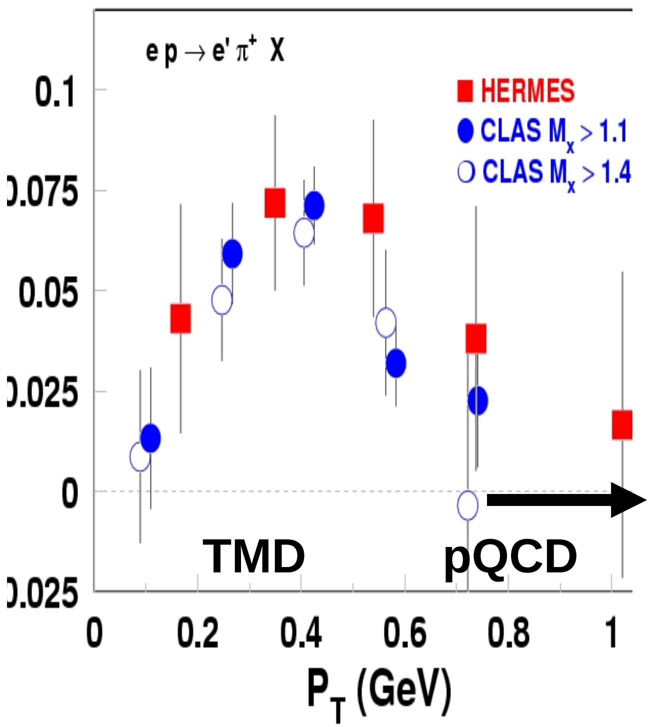
$\sigma^{\sin\phi}_{LU(UL)} \sim F_{LU(UL)} \sim 1/Q$ (Twist-3)

A_{UL} (CLAS @5.7 GeV)



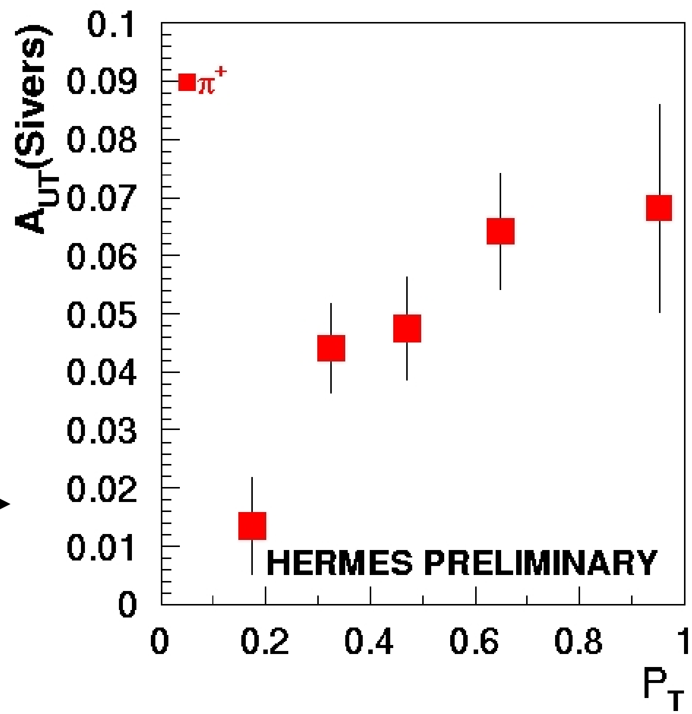
$$A_{UL}^{\sin\phi} \propto f_L^{\perp} D_1$$

A_{LU} CLAS @4.3 GeV



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

A_{UT} HERMES @27.5 GeV



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

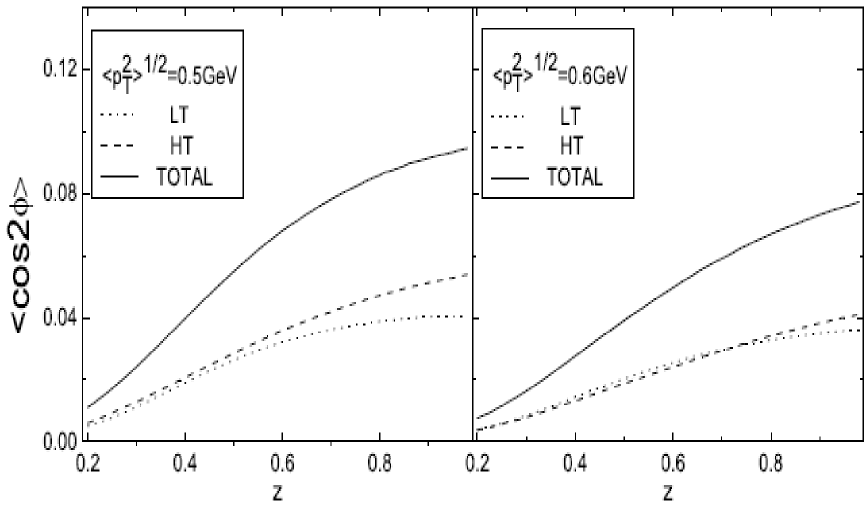
Beam and target SSA for π+ are consistent with increase with P_T
In the perturbative limit is expected to behave as $1/P_T$

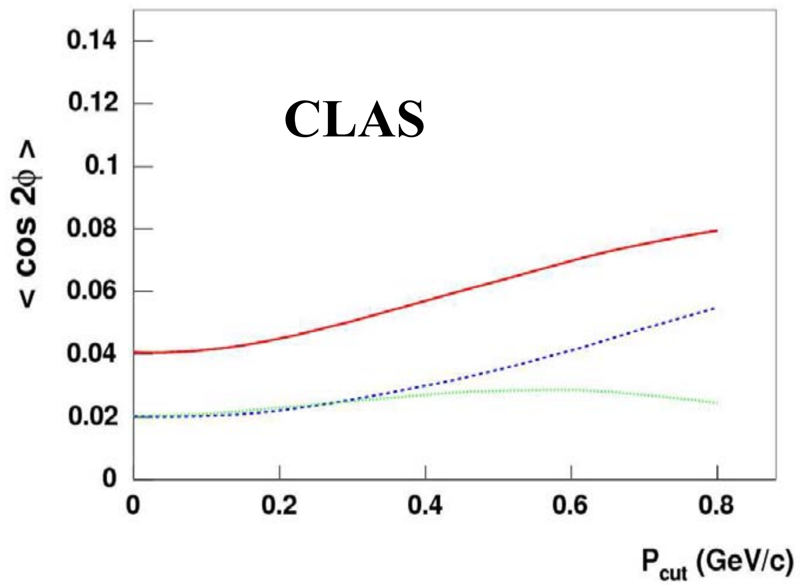
Azimuthal moments in SIDIS ($1/Q^2$)

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

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

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

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

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

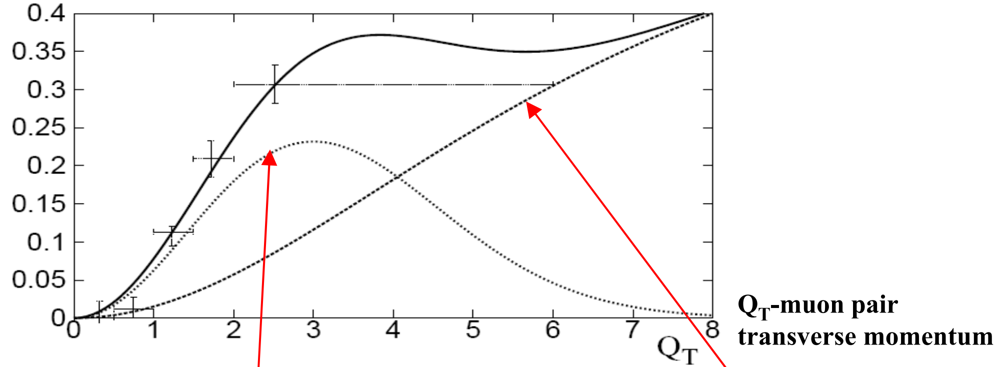


Figure 3. *Impression* of possible contributions to ν as function of Q_T compared to DY data of NA10 (for $Q = 8$ GeV). Dashed curve: contribution from perturbative one-gluon radiation. Dotted curve: contribution from a nonzero $h_1^\perp$. Solid curve: their sum.

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

with $M_C = 2.3\,\mathrm{GeV}$, $c_H^a = 1$ 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)

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

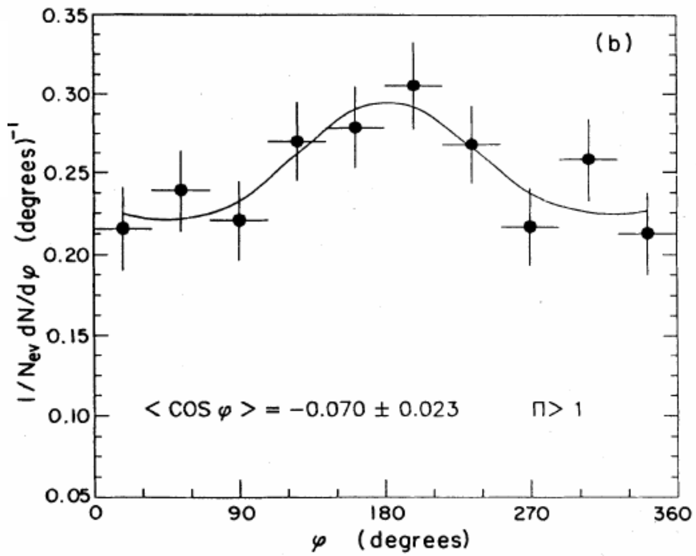
$$Q^2 > 3.0\text{GeV}^2/c^2 ,$$

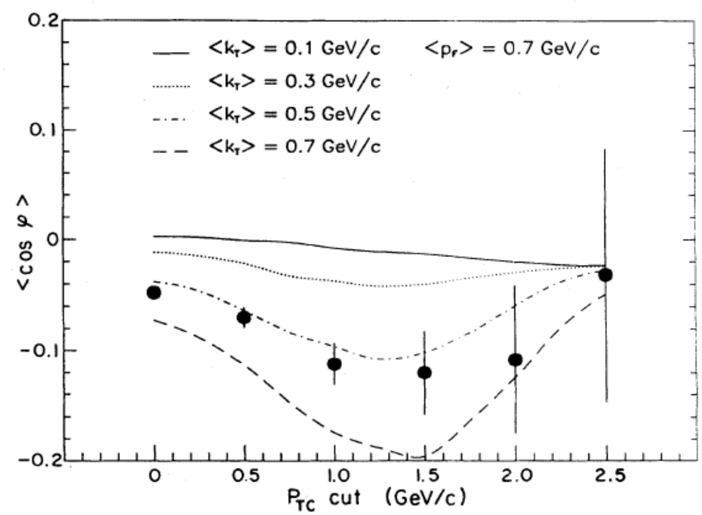
$$0.1 < y_{\text{Bj}} < 0.85 ,$$

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

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

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





SIDIS moments: EMC(1986)

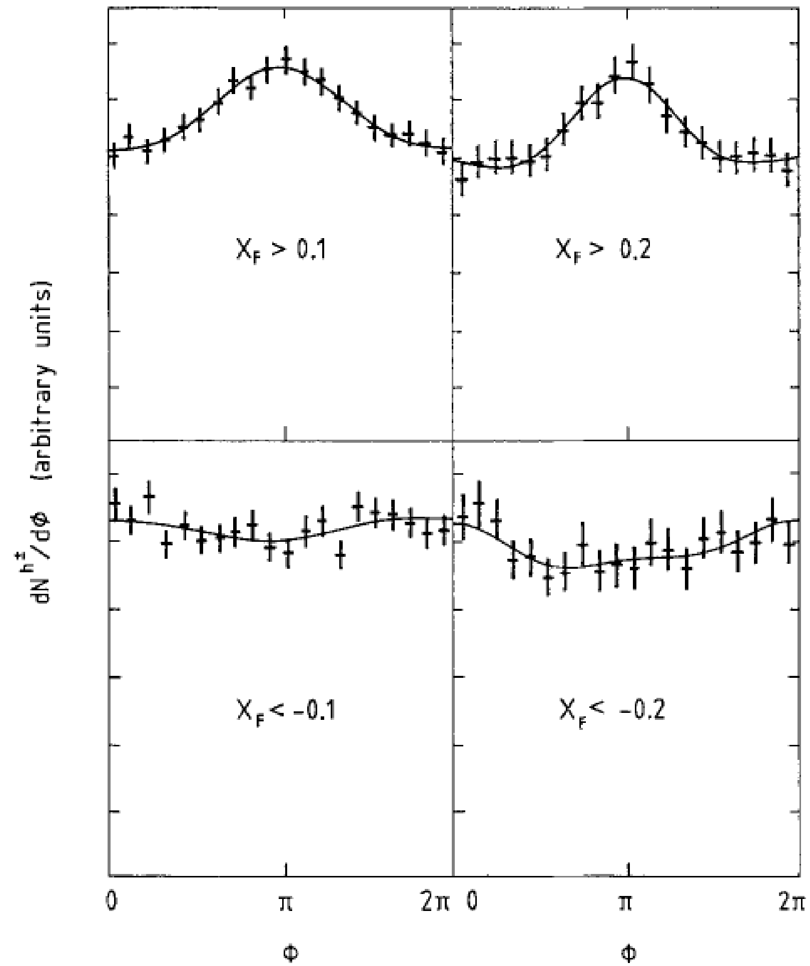
EMC experiment (280 GeV μp-27k)

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.

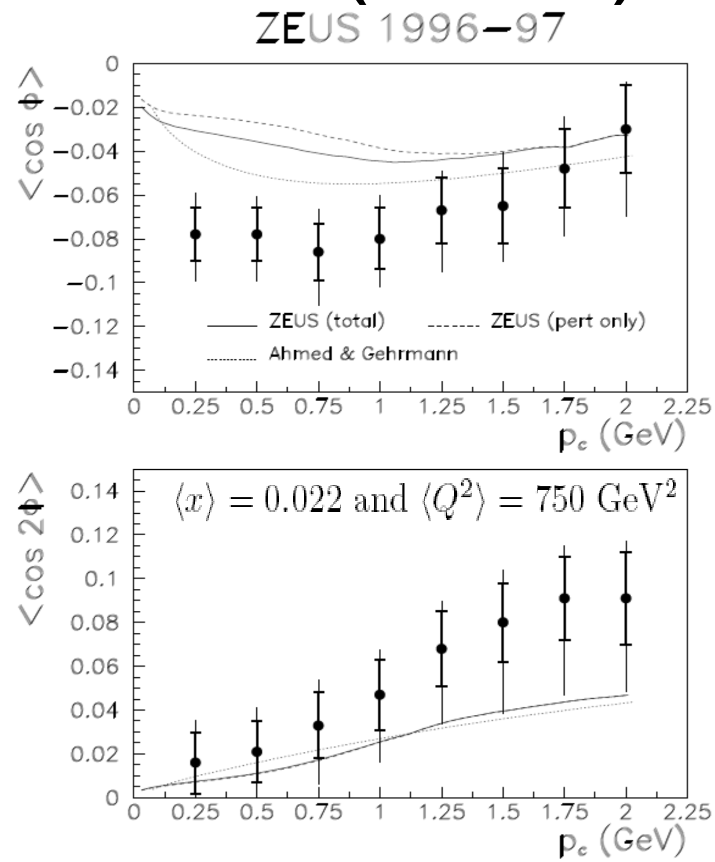


Figure 4: The values of $\langle \cos\phi \rangle$ and $\langle \cos 2\phi \rangle$ are shown as a function of p_c in the kinematic region $0.01 < x < 0.1$ and $0.2 < y < 0.8$ for charged hadrons with $0.2 < z_h < 1.0$. The inner error bars represent the statistical errors, the outer are statistical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

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. $0.2 < z_h < 1.0$

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