Studies of GPDs and TMDs at JLab

Harut Avakian (JLab)

COMPASS Seminar, March 29 2012

Outline

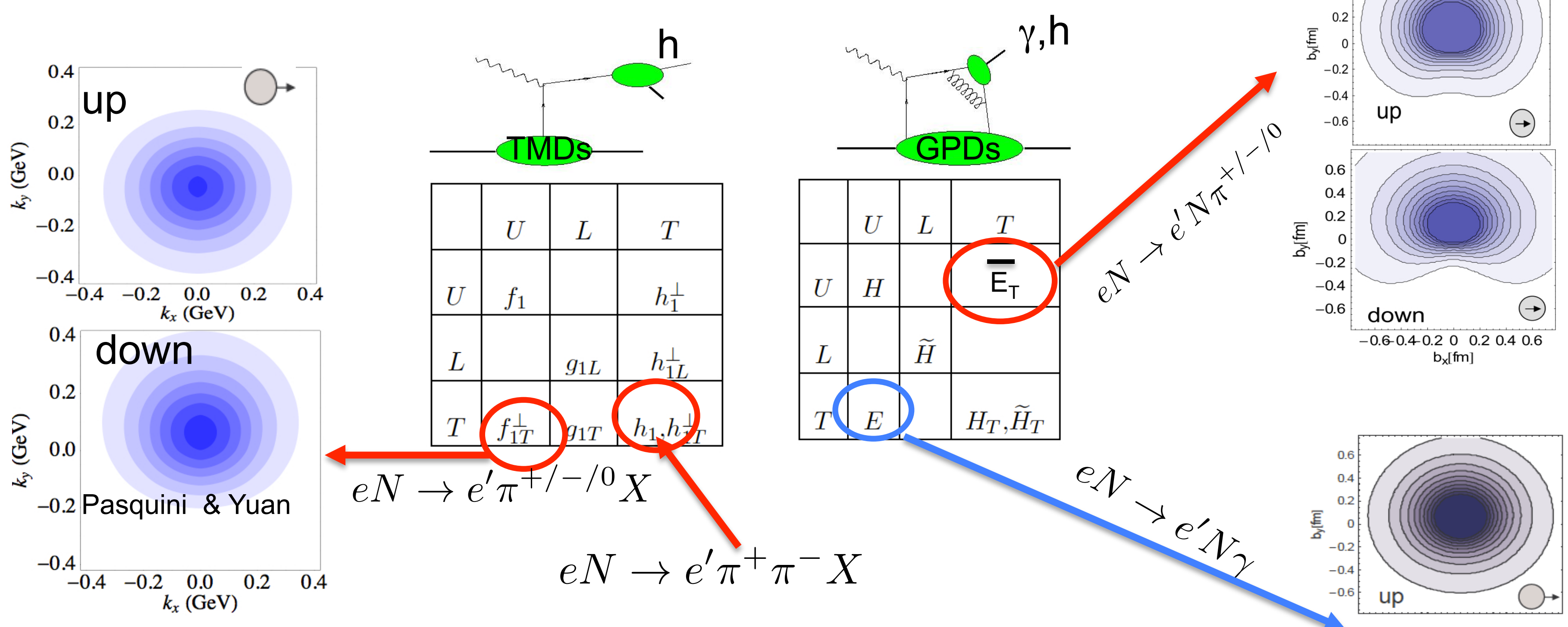
Transverse structure of the nucleon and partonic correlations

- Introduction
- k_T-effects with unpolarized and polarized target data
- SSA measurements and "puzzles"
- Studies of 3D PDFs at JLab at 6 GeV
- Hard exclusive processes and correlations between transverse degrees of freedom
- Studies of 3D structure of the nucleon at JLab12 and beyond
- Extracting transversity from di-hadron production
- Summary

3D structure of the nucleon

Semi-Inclusive processes and transverse momentum distributions

Hard exclusive processes and spatial distributions of partons



	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

	U	L	T
U	H		$\bar{E}_T$
L		$\widetilde{H}$	
T	E		$H_T, \widetilde{H}_T$

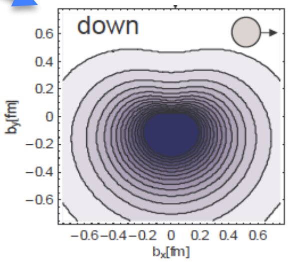
Pasquini & Yuan

$eN \to e'\pi^{+/-/0}X$

$eN \to e'\pi^+\pi^- X$

$eN \to e'N\pi^{+/-/0}$

$eN \to e'N\gamma$



(QCDSF)

- Wide kinematic coverage of large acceptance detectors allows studies of exclusive (GPDs) and semi-inclusive (TMDs) processes providing complementary information on transverse structure of the nucleon.

TMD Distributions: Theory

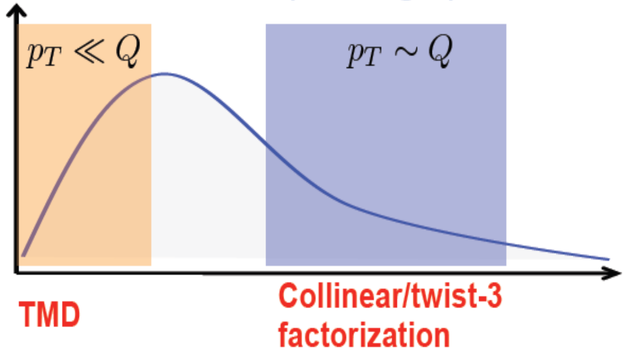
- Classification of TMDs and SIDIS and DY x-sections (Ralston,Soper 1979, Mulders,Tangerman,Kotzinian 1995)
- The role of final state interactions in SSA (Brodsky et al,Collins 2002)
- Universality of k_T-dependent distribution and fragmentation functions. Sign flip for $f_{1T}^{\perp}$, $h_1^{\perp}$ from DY to SIDIS predicted. (Collins,Metz 2003)
- Gauge invariant definition of k_T-dependent PDFs (Belitsky,Ji,Yuan 2003)
- Factorization proven for small k_T (Ji,Ma,Yuan 2005)
- Complete definition of TMDs (Collins 2011 "Foundation of Perturbative QCD")
- Evolution of TMDs, (Collins,Aybat,Rogers 2011)
- TMDs on Lattice, (Musch, Haegler et al. 2011)
- Fracture Functions and SIDIS x-sections (Trentadue,Veneziano 1974, Anselmino, Barone, Kotzinian 2011)
- k_T-dependent flavor decomposition (BGMP procedure,2011)

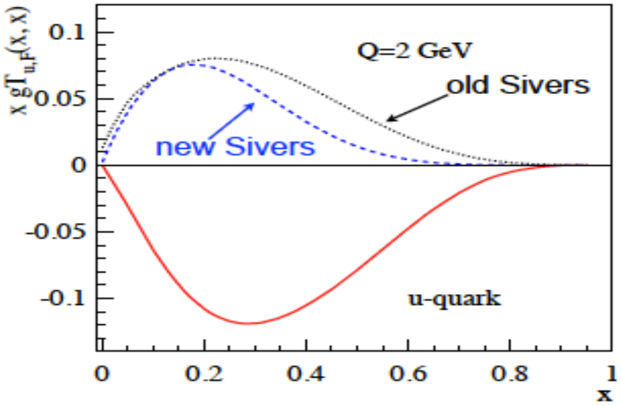
Generalized Parton Distributions: Theory

- Introduction of GPDs (D.Mueller et al 1994, X.Ji 1996, Radyushkin 1997)
- Decomposition of the OAM (X.Ji 1997)
- Factorization for hard exclusive electroproduction of mesons in QCD (Collins,Frankfurt & Strikman 1996)
- Transversity GPDs (Hoodbhoy & Ji 1998, M. Diehl 2001)
- Transverse space interpretation (Burkardt 2000, Ralston&Pire 2001, Diehl 2003, Diehl & Haegler (2005)
- GPDs from DVCS and DVMP (Ji 1996, Mueller 2001,VGG 1999)
- GPDs on Lattice, (QCDSF, Haegler et al. 2006)
- GPD (CFF extraction from DVCS data (D. Mueller, M. Guidal, H. Mutarde,…)
- Accessing transversity GPDs in DVMP (Liuti&Goldstein 2008, Kroll&Goloskokov 2010)

k_T-dependence of TMDs

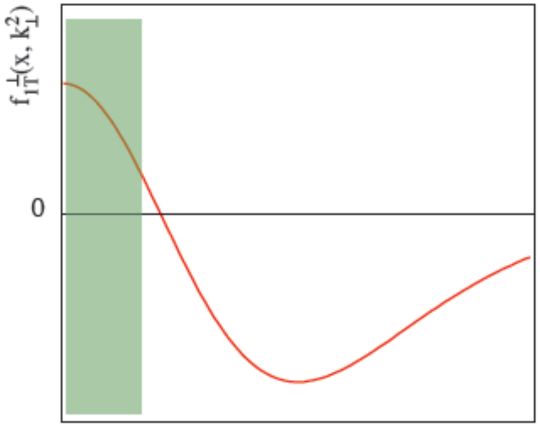
- Transition from low p_T to high p_T

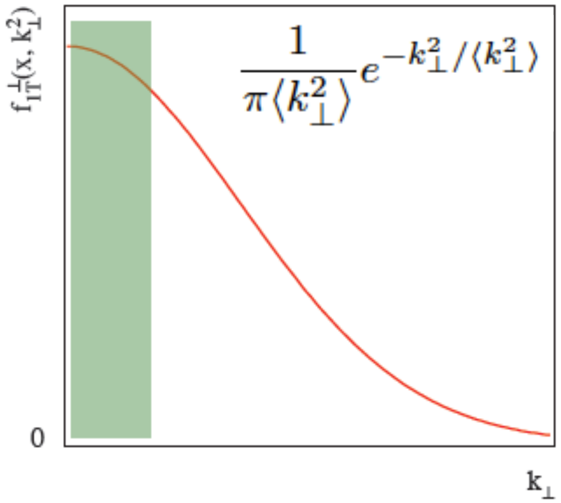




Directly obtained ETQS functions are opposite in sign to those from k_T moments "sign mismatch"

Sivers function extracted assuming k_T distribution is gaussian

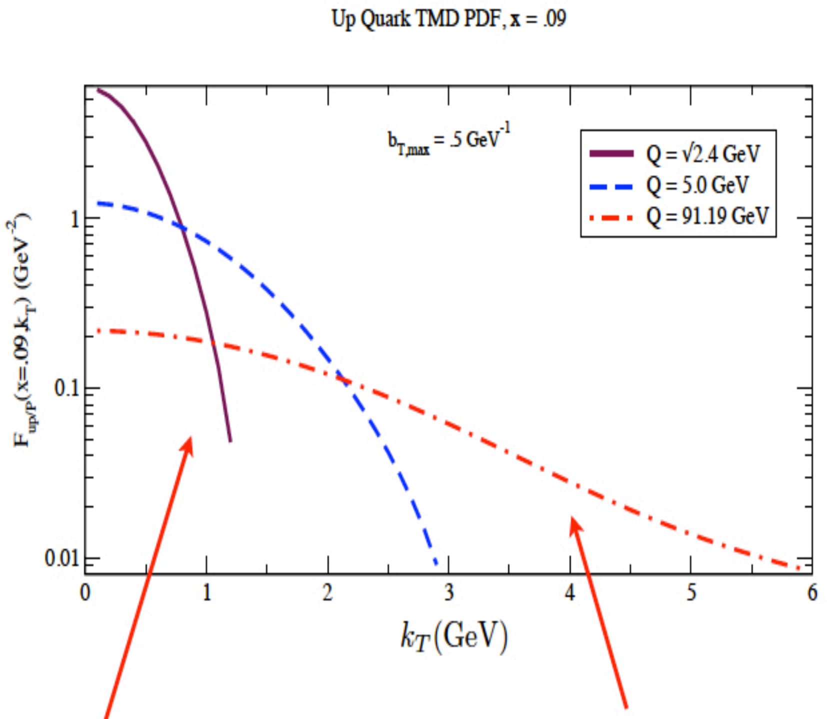




- With orbital angular momentum TMD can't be gaussian
- How to measure k_T-dependences of TMDs

(Z. Kang et al, 2011)

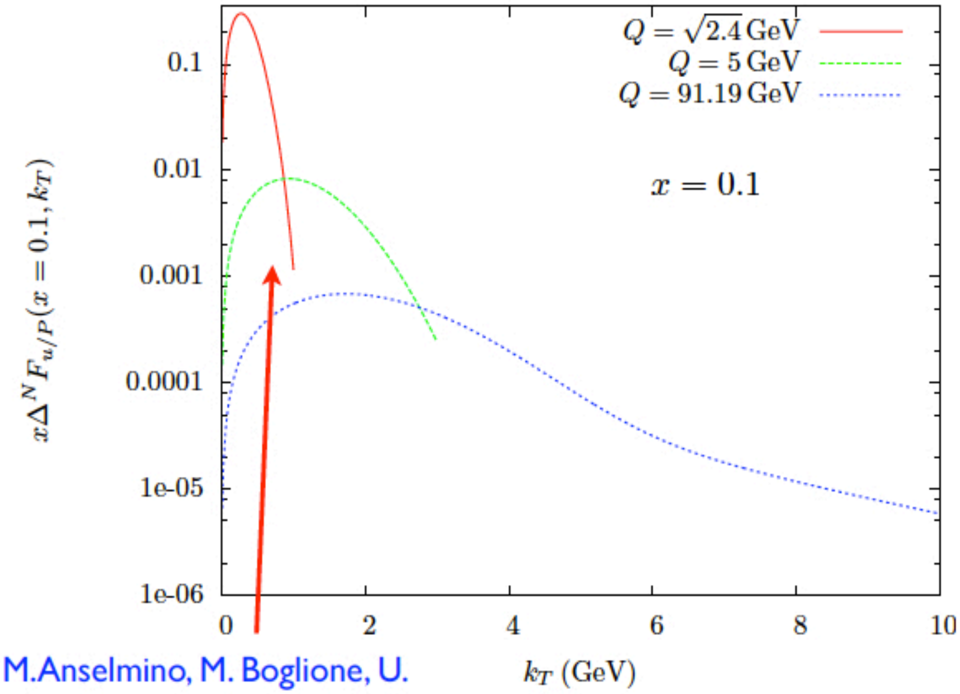
TMD evolution



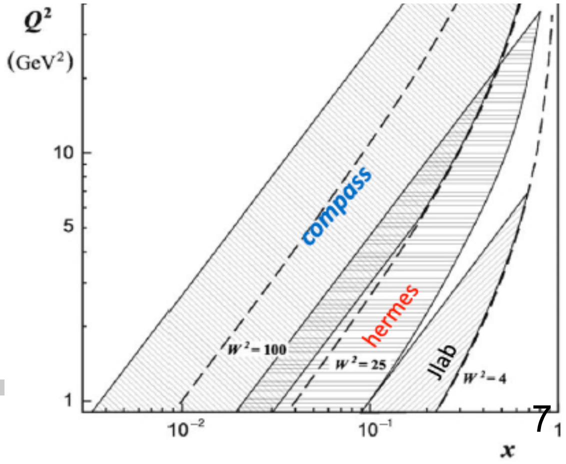
JLab Energies
matches STM fit

Tevatron Energies
matches BNLY fit

Brock,Landry,Nadolsky,Yuan (2003) (BLNY)



M.Anselmino, M. Boglione, U. D'Alesio, A.Kotzinian, S.Melis, F. Murgia, A. Prokudin, C.Turk; 2009

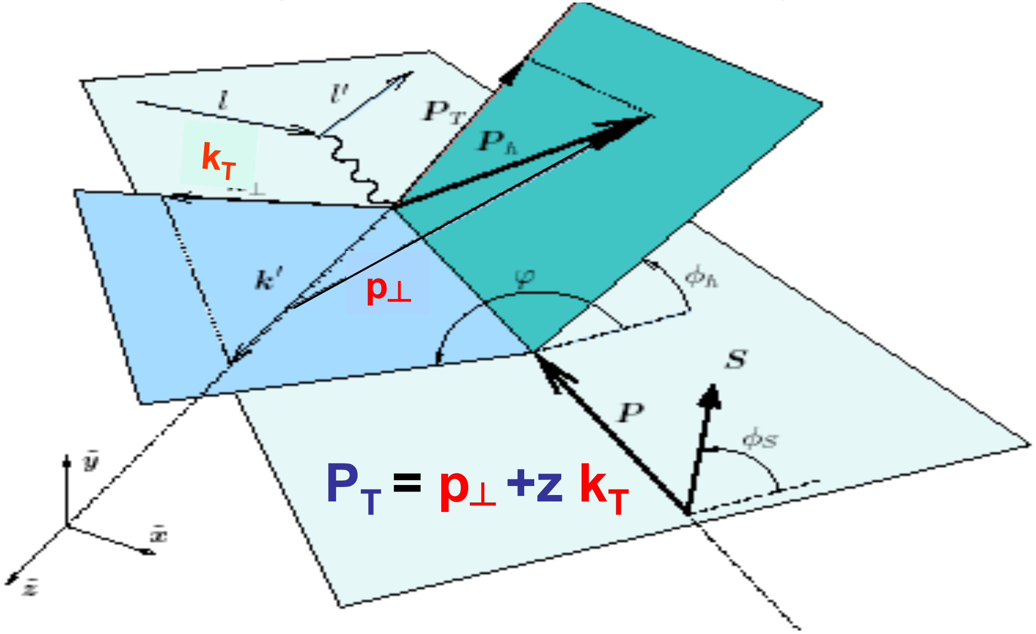


Q^2 evolution of Sivers asymmetry may be very significant

SIDIS: partonic cross sections

$$\nu = (qP)/M$$
$$Q^2 = (k - k')^2$$
$$y = (qP)/(kP)$$
$$x = Q^2/2(qP)$$
$$z = (qP_h)/(qP)$$

$$\sigma = F_{UU} + P_t F_{UL}^{\sin\phi} \sin 2\phi + P_b F_{LU}^{\sin\phi} \sin\phi \ldots$$



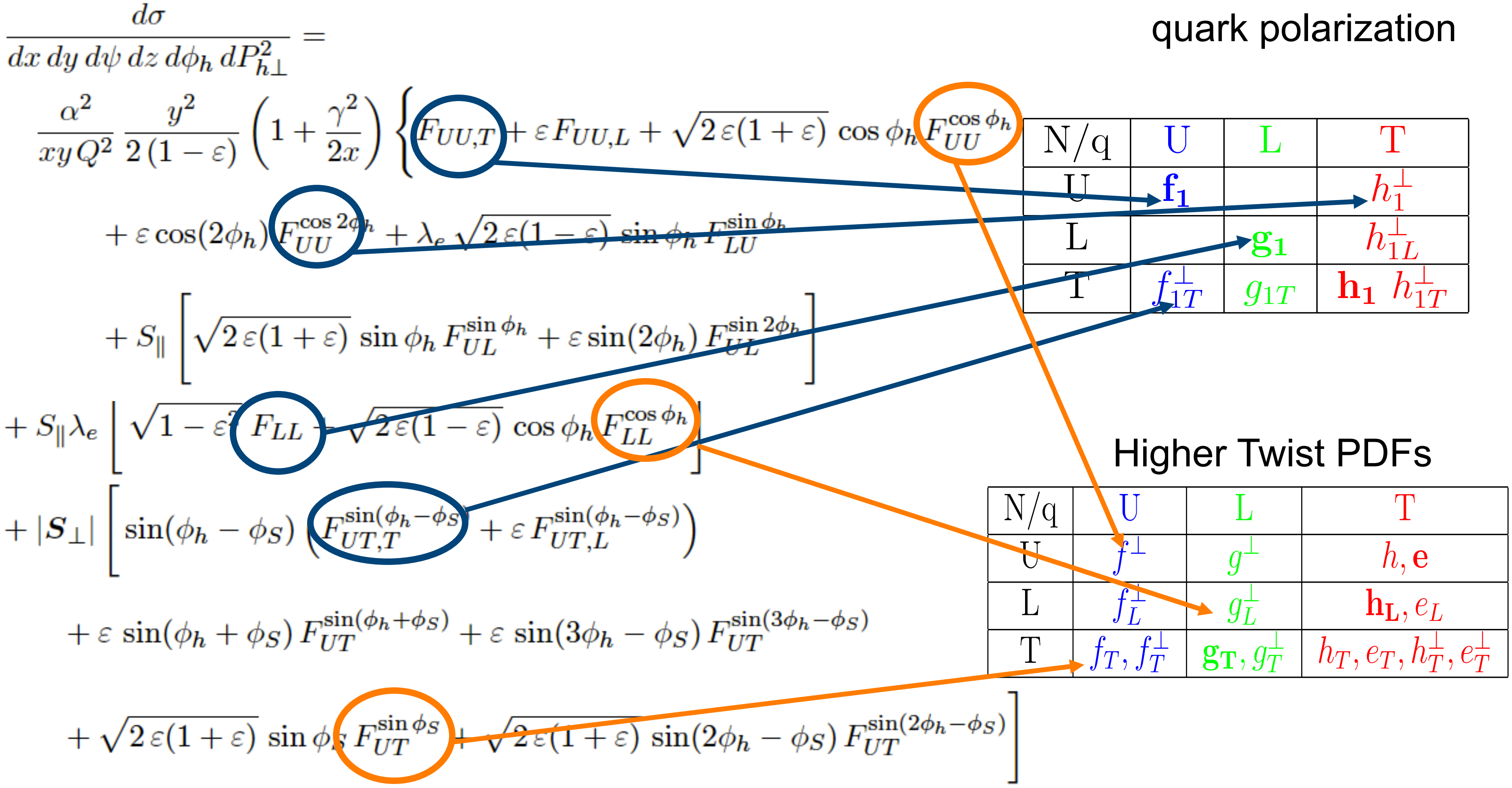
$P_T = p_\perp + z\, k_T$

Transverse momentum of hadrons in SIDIS provides access to orbital motion of quarks

Ji,Ma,Yuan Phys.Rev.D71:034005,2005

$$d\sigma^h \propto \sum e_q^2 \int d^2\vec{k}_T d^2\vec{p}_T d^2\vec{l}_T f^{H\to q}(x, k_T) D^{q\to h}(z, p_\perp) S(\vec{l_T}) H(Q) \delta(z\vec{k}_T + \vec{p}_T + \vec{l}_T - \vec{P}_T)$$

Azimuthal moments in SIDIS



$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$$+\,S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]$$

$$+\,S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

$$+\,|\boldsymbol{S}_\perp|\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\,\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg]$$

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

$$+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\},$$

quark polarization

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

Higher Twist PDFs

N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

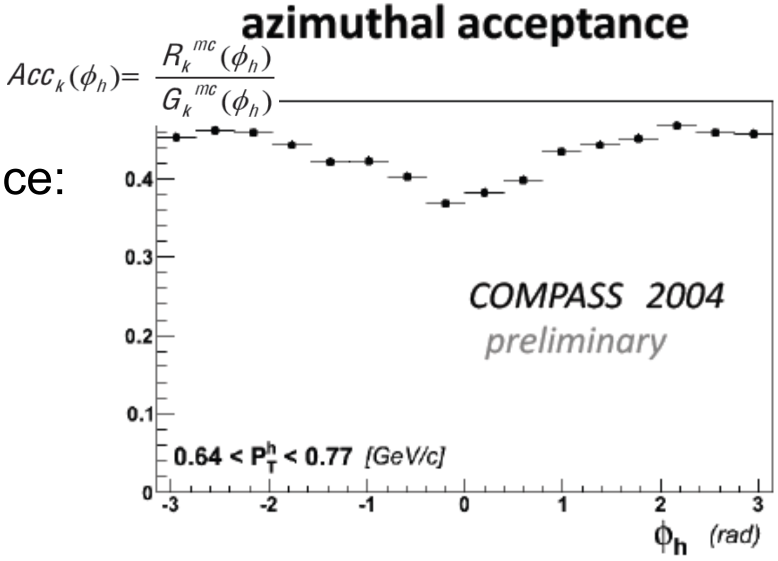
Experiment for a given target polarization measures all moments simultaneously

Extracting the moments

Moments mix in experimental azimuthal distributions

Simplest acceptance -> $1 + A\cos\phi$

Acceptance:



Correction to normalization

$$(1+\alpha\cos\phi)(1+A\cos\phi) \rightarrow 1 + A\alpha/2$$

$$(1+\beta\lambda\Lambda+\gamma\lambda\Lambda\cos\phi)(1+A\cos\phi)$$
$$\rightarrow 1 + (\beta+\gamma A/2)\lambda\Lambda$$

Correction to DSA

$$(1+S_T\delta\sin\phi_S)(1+A\cos\phi)$$
$$\rightarrow 1 + S_T/2\delta A(\sin\phi-\phi_S) + \ldots$$

Correction to SSA

Moments/asymmetries:

$$\frac{1+\beta\lambda\Lambda}{1+a\cos\phi} \rightarrow 1 - a\beta\lambda\Lambda\cos\phi$$

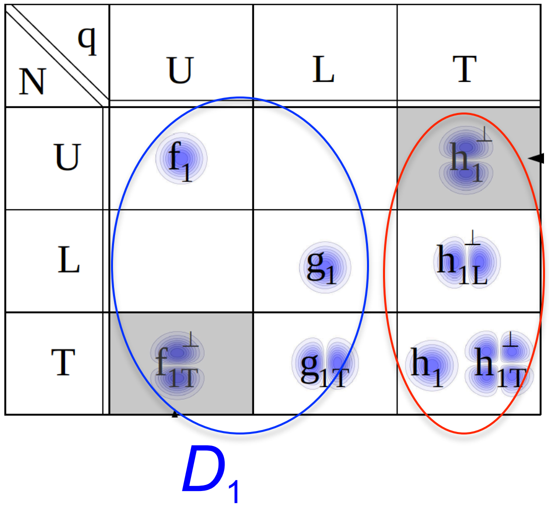
Fake DSA cos

Virtual photon angle:

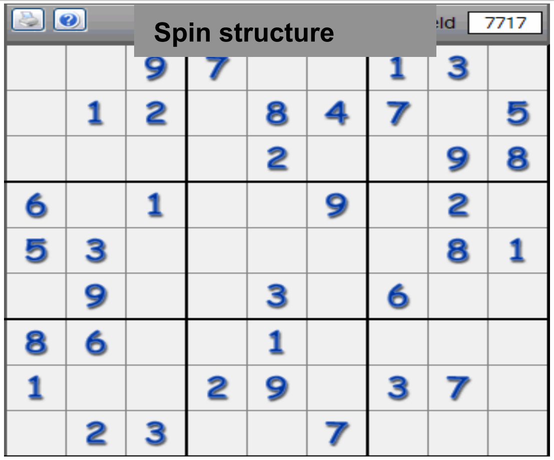
$$\sin\theta_\gamma = \sqrt{\frac{4M^2x^2}{Q^2+4M^2x^2}\left(1-y-\frac{M^2x^2y^2}{Q^2}\right)}$$

Simultaneous extraction of moments is important also because of correlations!

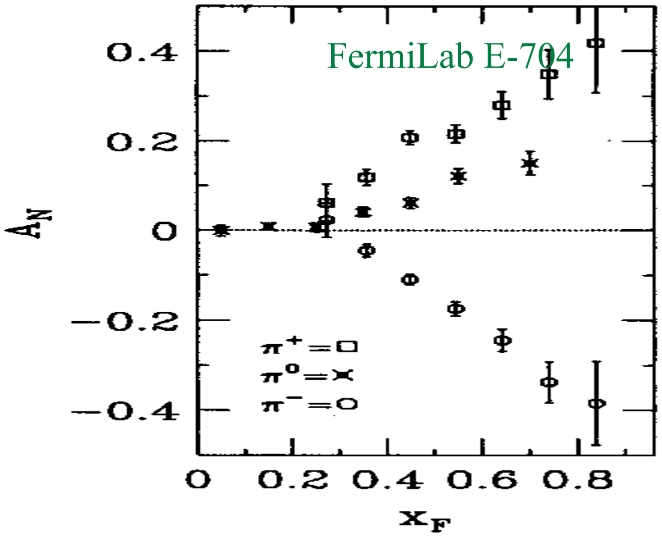
TMD Distributions: First experiments

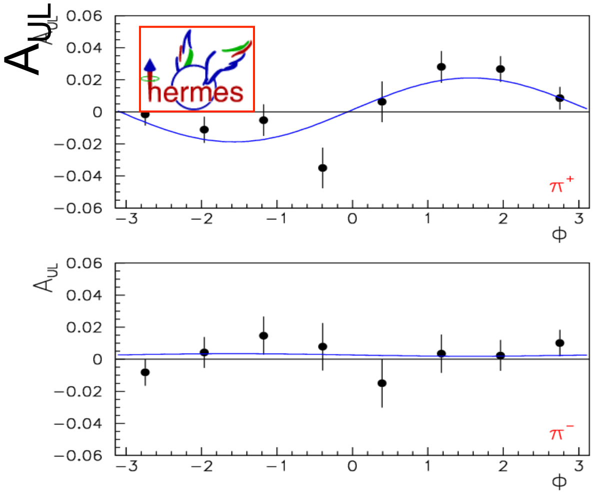


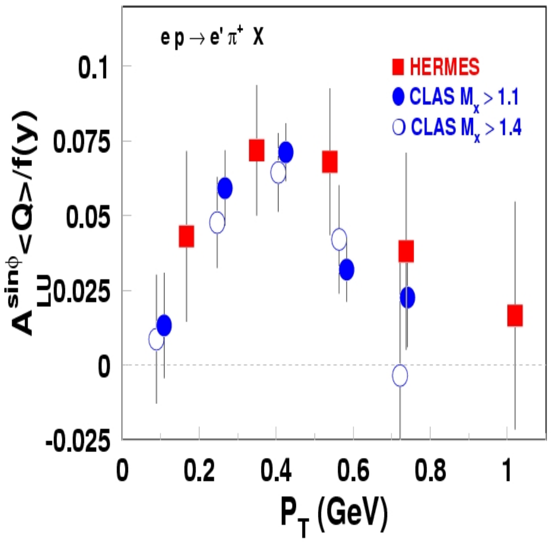
$H_1^\perp$ →



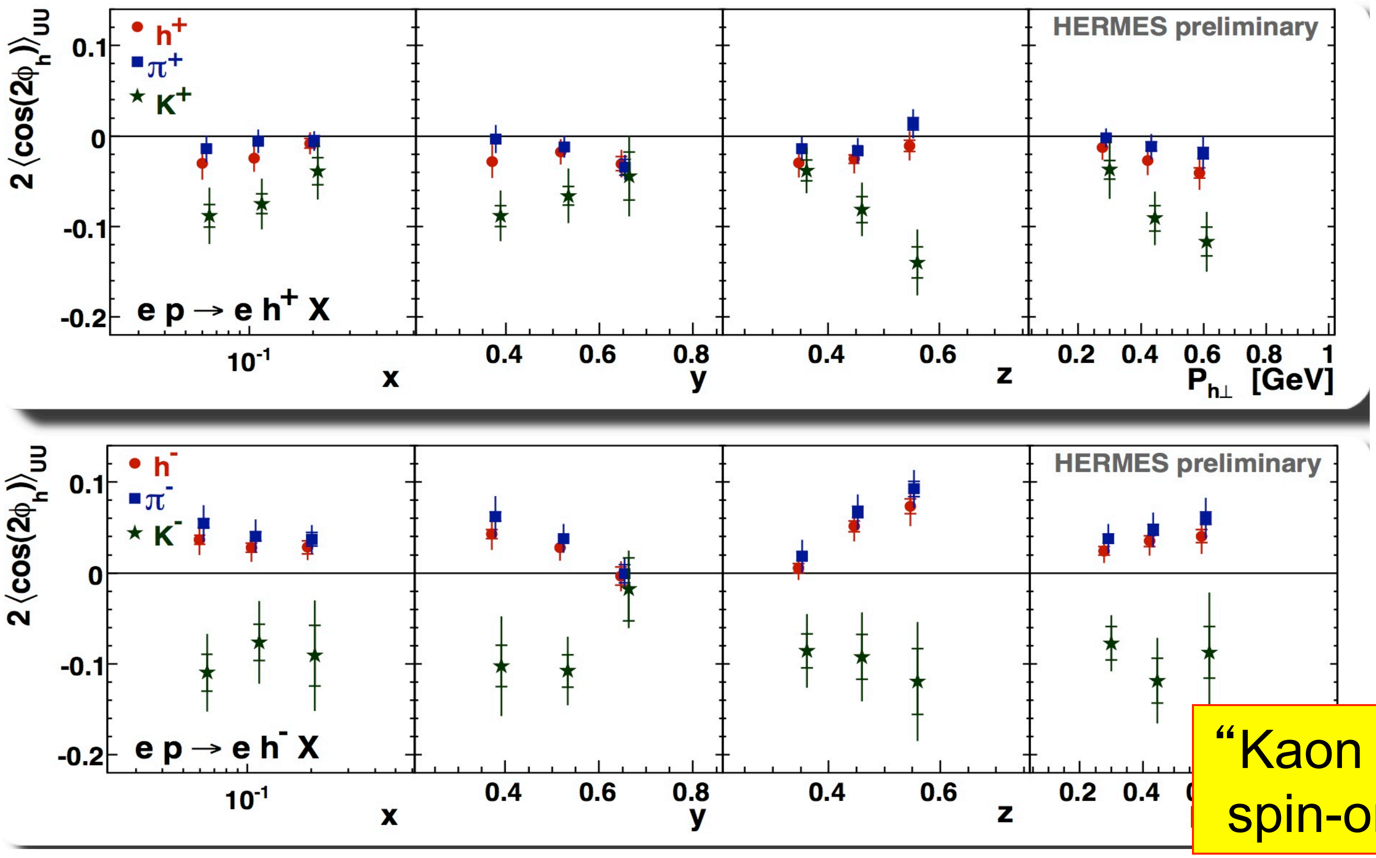
		9	7			1	3	
	1	2		8	4	7		5
				2			9	8
6		1			9		2	
5	3						8	1
	9			3		6		
8	6			1				
1			2	9		3	7	
	2	3			7			







Kaon <cos2ϕ> @ HERMES

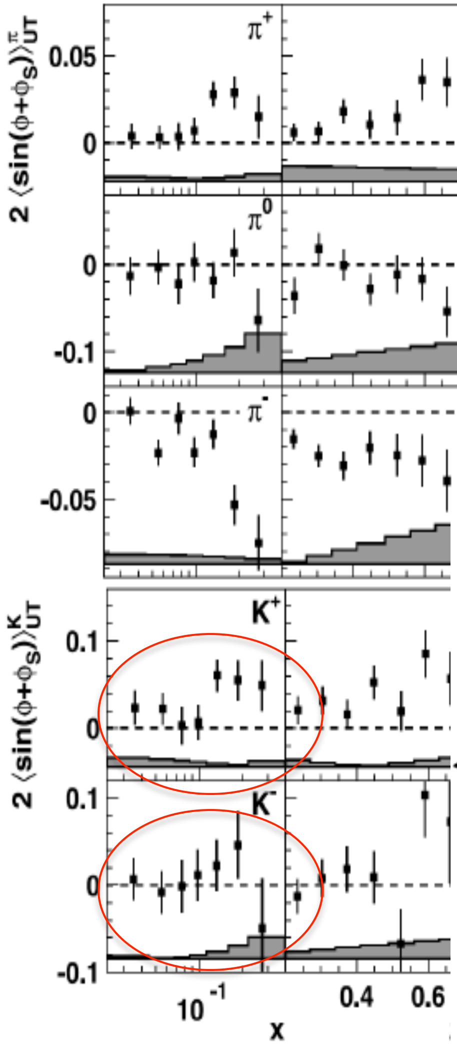


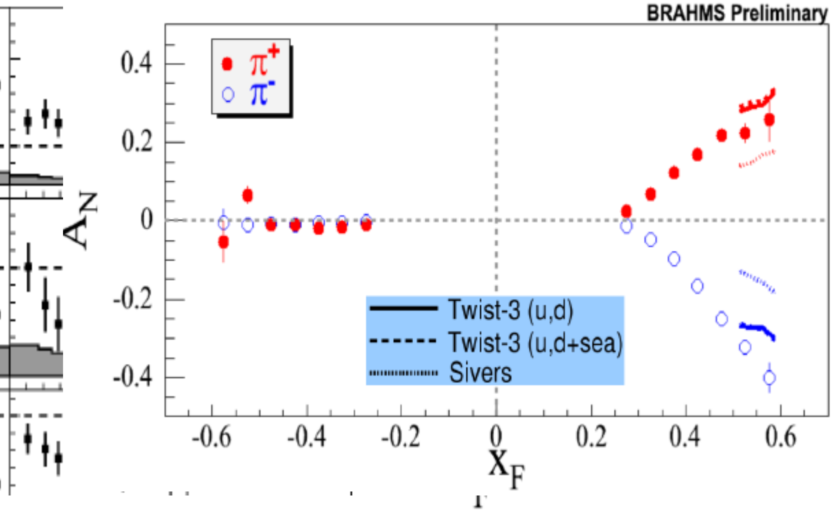
$$h_1^{\perp} H_1^{\perp}$$

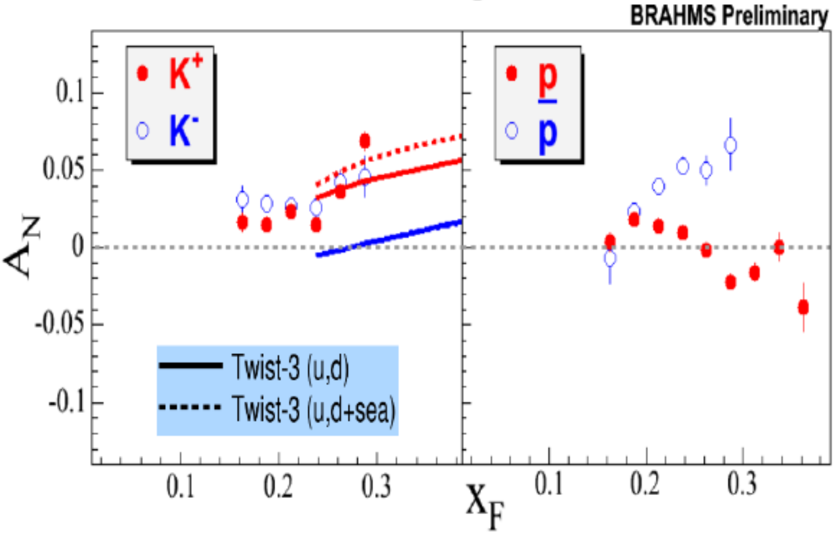
“Kaon puzzle” in spin-orbit correlations

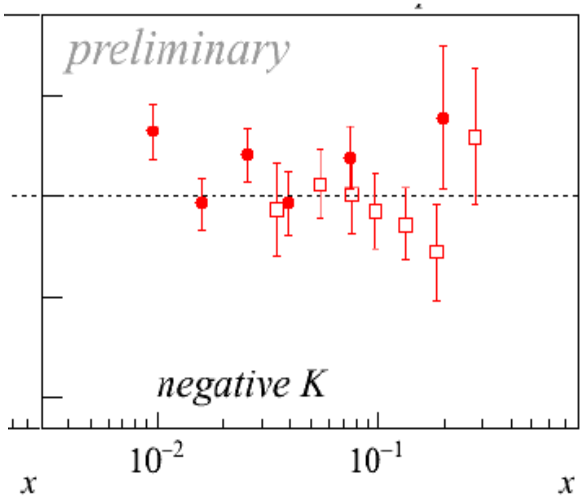
- $u-dominance$ $K^+\{u\bar{s}\}$ $\pi^+\{u\bar{d}\}$ $\xrightarrow{?}$ $\dfrac{H_1^{\perp,u\rightarrow K^+}}{D_1^{u\rightarrow K^+}} > \dfrac{H_1^{\perp,u\rightarrow \pi^+}}{D_1^{u\rightarrow \pi^+}}$
- Relative sign $H_1^{\perp\,fav}$ / $H_1^{\perp\,unfav}$ for π and K inconsistent

Dedicated experiments to study TMDs



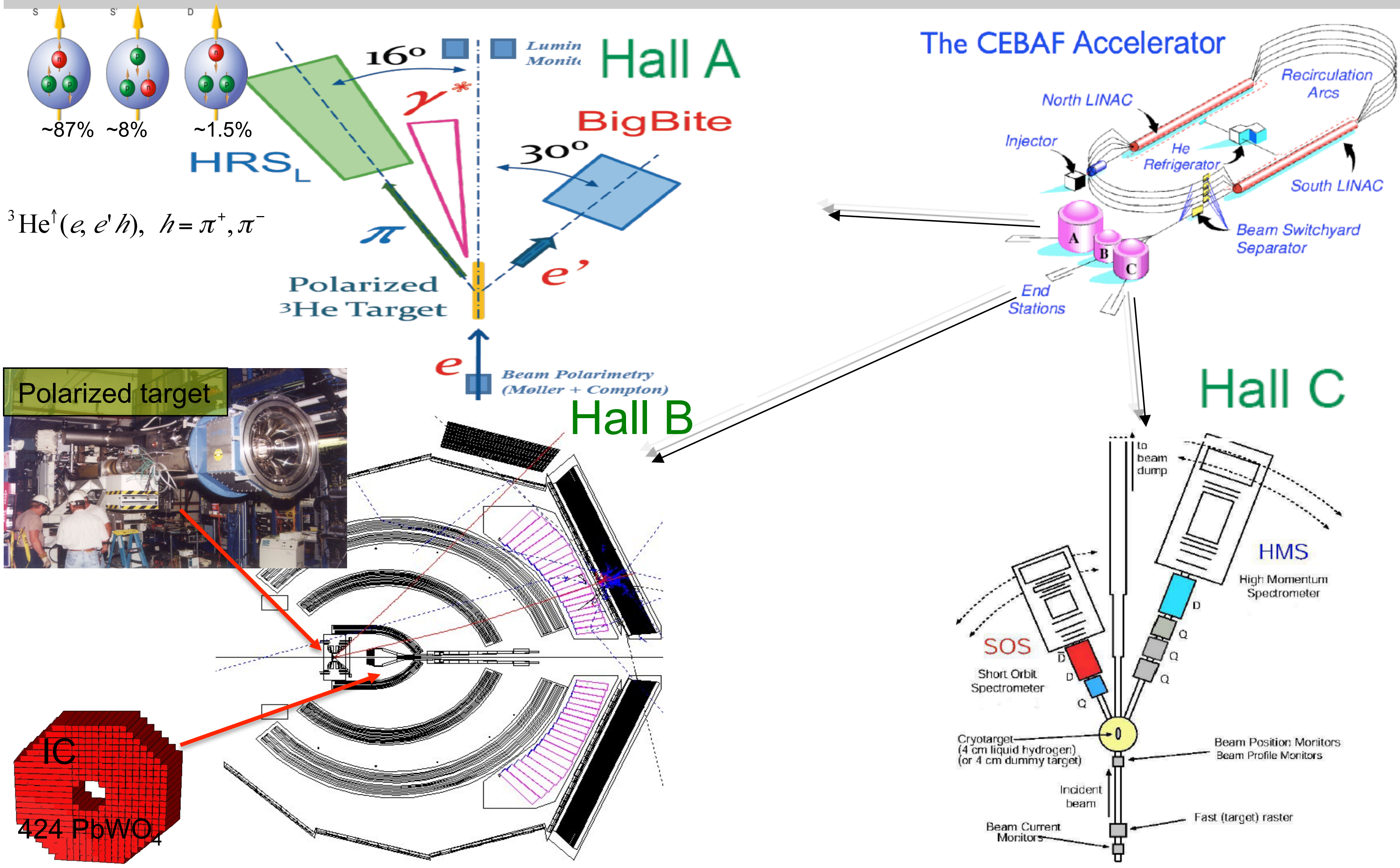






Is there a link between HERMES and BRAHMS Kaon vs pion moments (K- has the same sign as K+ and π+, comparable with K+)?

JLab Experimental Halls



$^3\mathrm{He}^{\uparrow}(e, e'h),\ h=\pi^+,\pi^-$

P_T-dependence studies at Hall-C

H. Mkrtchyan(DIS2011)

Experiment E00-108

Beam energy 5.5 GeV

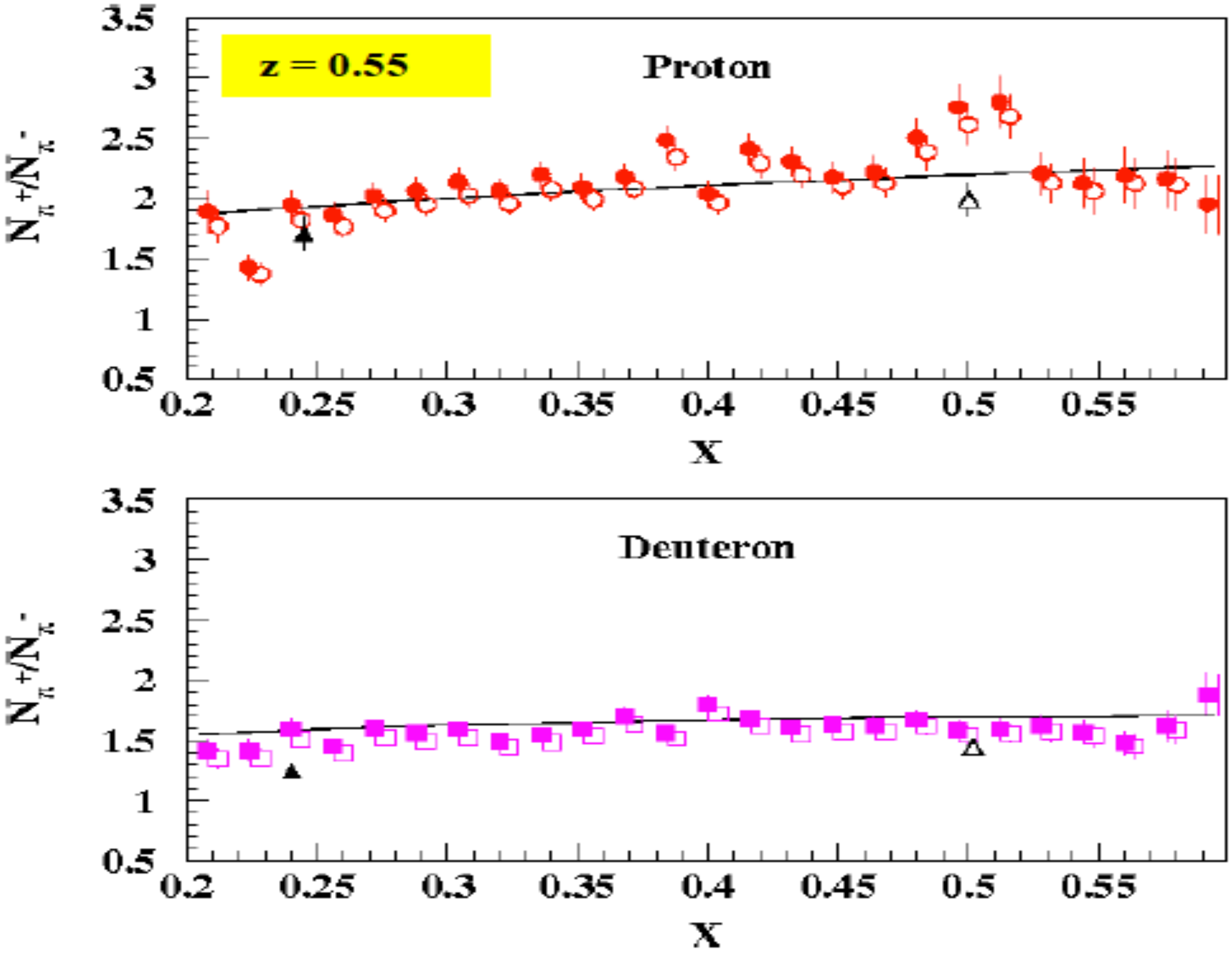
4 cm LH2 and LD2 targets

$$\sigma_d^{\pi^+} \propto (4D^+ + D^-)(u+d)$$

$$\sigma_d^{\pi^-} \propto (4D^- + D^+)(u+d)$$

$$\frac{\sigma_d^{\pi^+}}{\sigma_d^{\pi^-}} = \frac{4D^+ + D^-}{4D^- + D^+}$$

$$D^-/D^+ = (4 - r) / (4r - 1)$$
$$r = \sigma_d(\pi^+)/\sigma_d(\pi^-)$$



x-dependence of p+/p- ratio is good agreement with the quark parton model predictions (lines CTEQ5M+BKK).

P_T-dependence studies at Hall-C

H. Mkrtchyan(DIS2011)

Experiment E00-108

Beam energy 5.5 GeV

4 cm LH2 and LD2 targets

$P_t = p_t + zk_t$

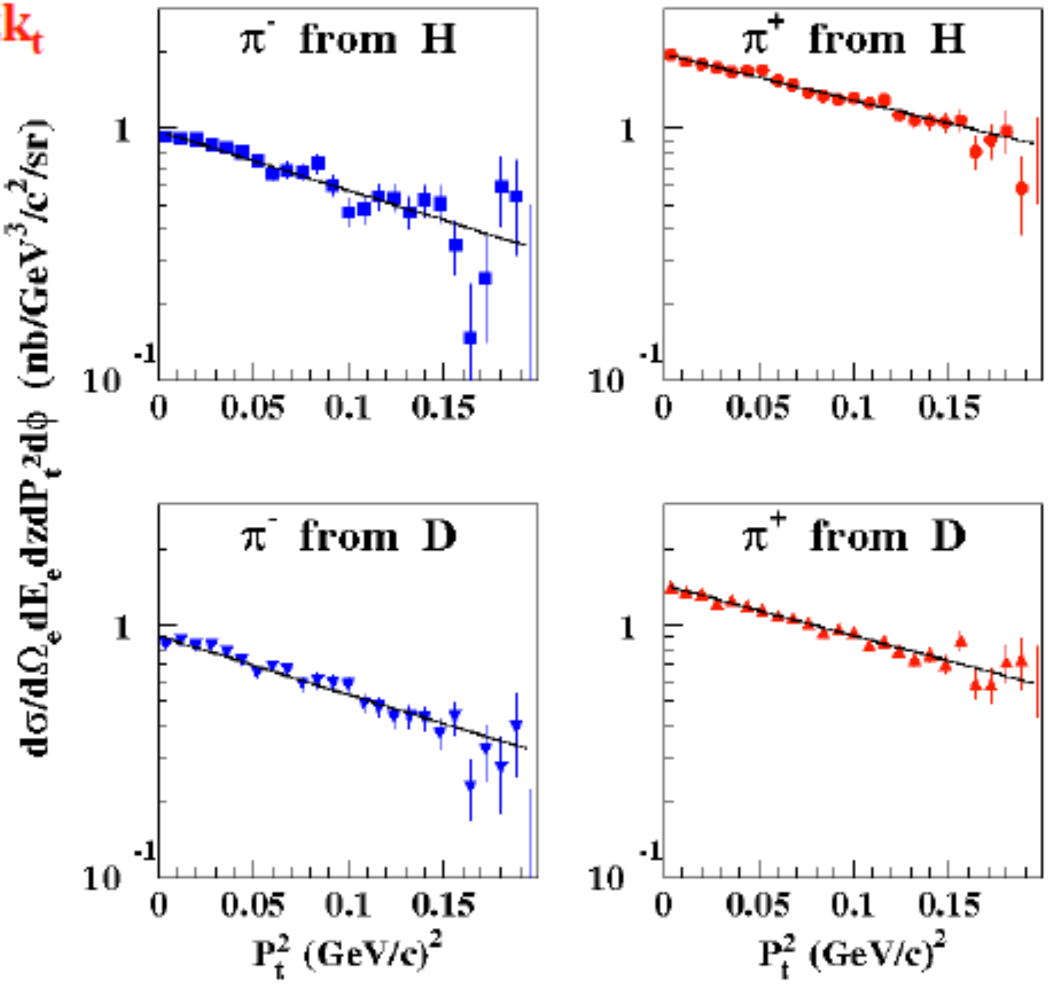
$\sigma_{SIDIS} \sim \sigma_{DIS} (dN/dz)\ b \exp(-bP_t^2)$

$b_H^- = 5.44 \pm 0.36$

$b_D^- = 5.35 \pm 0.26$

$b_H^+ = 4.24 \pm 0.17$

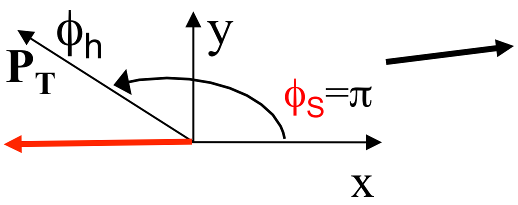
$b_D^+ = 4.64 \pm 0.17$



Data (assuming only valence quarks and only two fragmentation functions contribute) indicate that k_T-width of u-quarks is larger than for d-quarks

HT-distributions in SIDIS

$F_{LU}^{\sin\phi}$

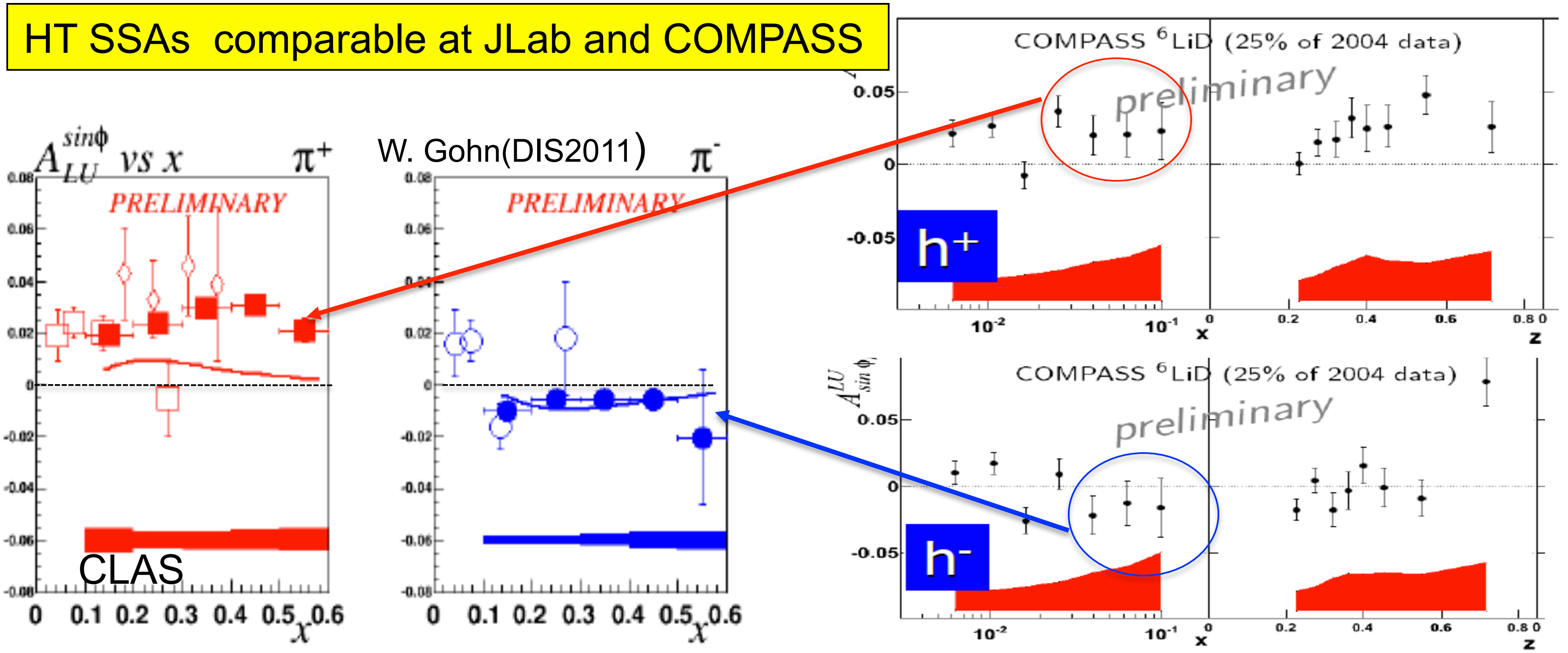


$eH_1^\perp$

HT function related to force on the quark. Burkardt (2008),Qiu(2011)

C.Schill(DIS2011)

HT SSAs comparable at JLab and COMPASS



Factorization of higher twists in SIDIS not proved

To study HT pdfs with dihadron SIDIS (replace $H_1^\perp$ with IFF PRD69 (2004))

$H_1^{\sphericalangle}$

Forces and binding effects in the partonic medium

$$xe = x\tilde{e} + \frac{m}{M} f_1$$

Interaction dependent parts

$$xh_L = x\tilde{h}_L + \frac{p_T^2}{M^2} h_{1L}^{\perp} + \frac{m}{M} g_{1L}$$

“Wandzura-Wilczek approximation” is equivalent to setting functions with a tilde to zero.

N/q	U	L	T
U			e
L			h_L
T		g_T	

$$e_2 \equiv \int_0^1 dx x^2 \tilde{e}(x)$$

Quark polarized in the x-direction with k_T in the y-direction

$$F^y(0) = \frac{M^2}{2} e_2$$

Boer-Mulders Force on the active quark right after scattering (t=0)

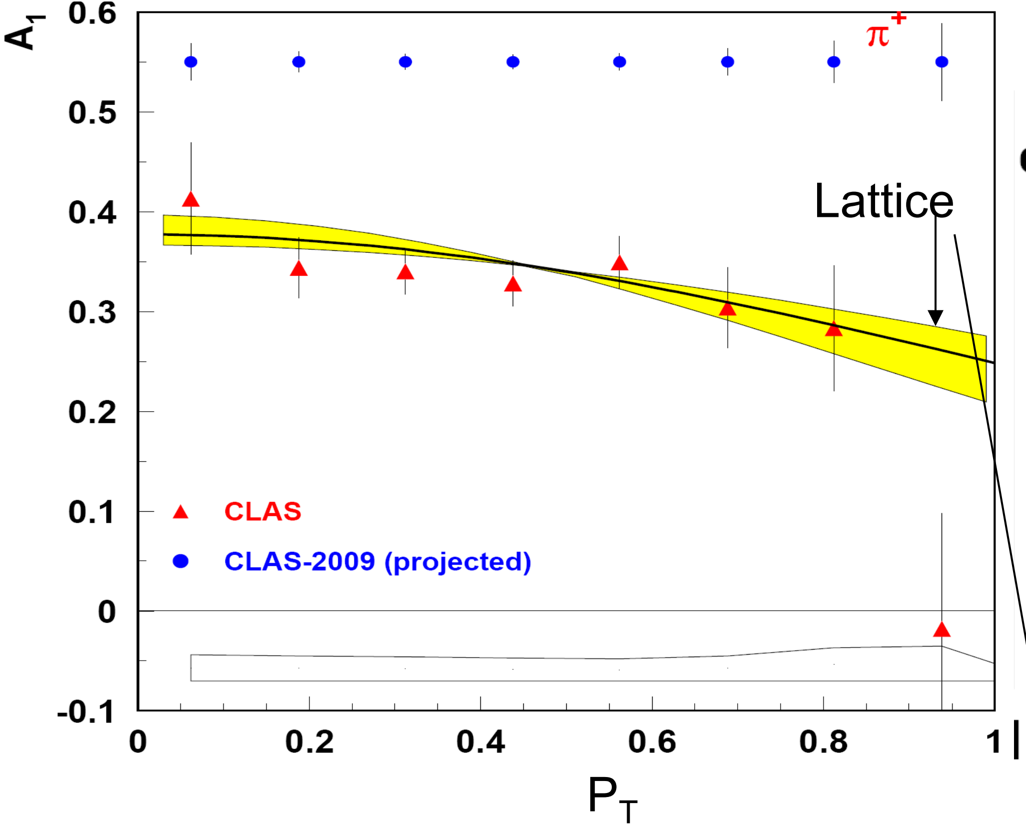
Interpreting HT (quark-gluon-quark correlations) as force on the quarks (Burkardt hep-ph:0810.3589)

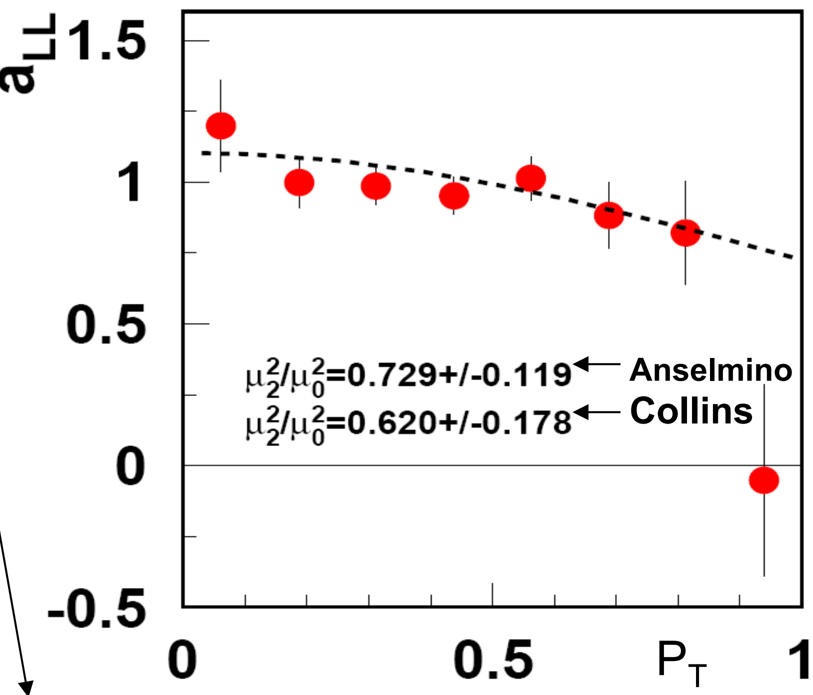
A_1 P_T-dependence

arXiv:1003.4549

$$A_1(\pi) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)}$$

$$A_1(x,z,P_T) = A_1(x,z)\underbrace{\frac{\langle P_T^{2,unp}\rangle}{\langle P_T^{2,pol}\rangle}\exp(-P_T^2/\langle P_T^{2,pol}\rangle - P_T^2/\langle P_T^{2,unp}\rangle)}_{a_{LL}}$$



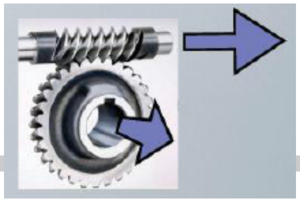


$\mu_2^2/\mu_0^2 = 0.692 \pm 0.039 \pm 0.045$

CLAS data suggests that width of g_1 is less than the width of f_1

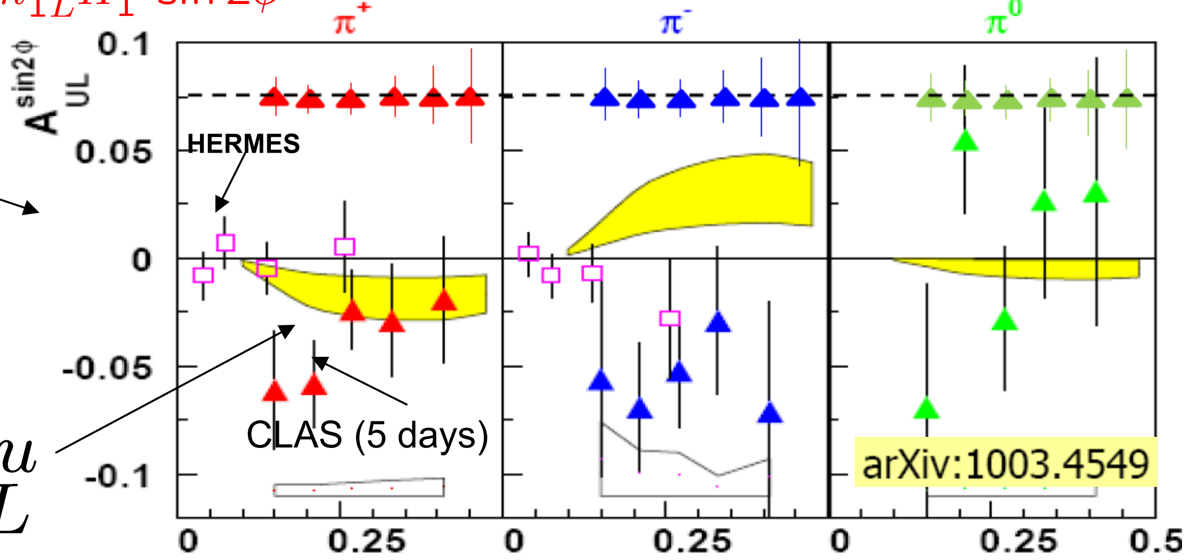
New CLAS data would allow multidimensional binning to study k_T-dependence for fixed x

Kotzinian-Mulders Asymmetries



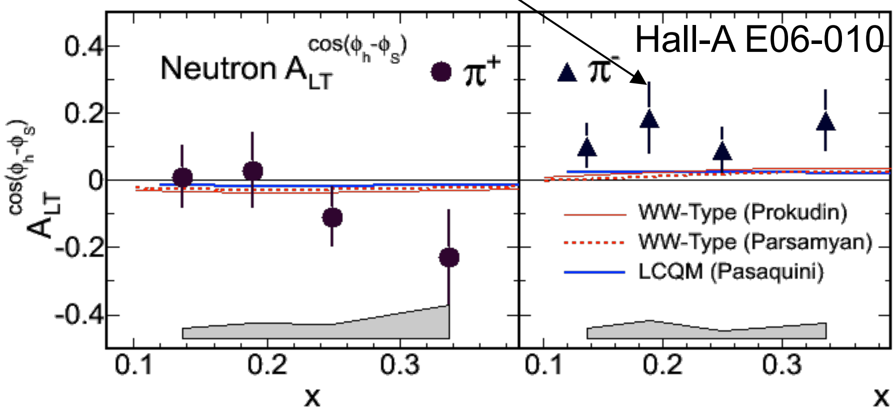
N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

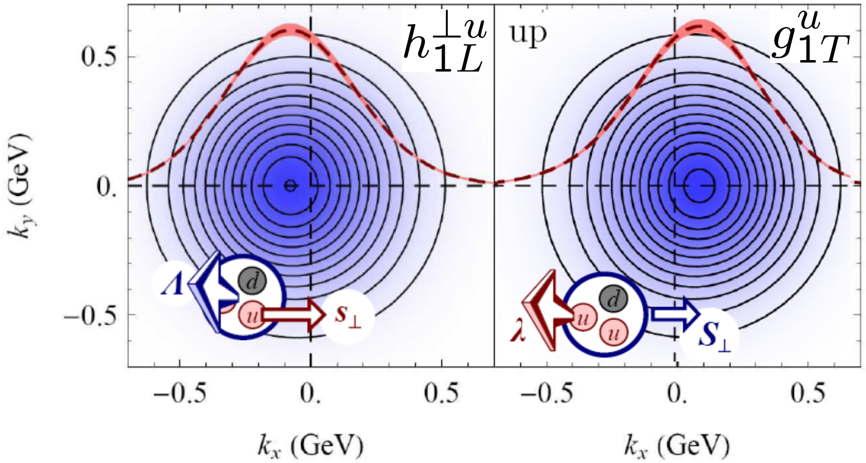
$$A_{UL}^{\sin 2\phi} \sim h_{1L}^{\perp} H_1^{\perp} \sin 2\phi$$



$$g_{1T}^{u} \approx -h_{1L}^{\perp u}$$

J. Huang (DIS2011)



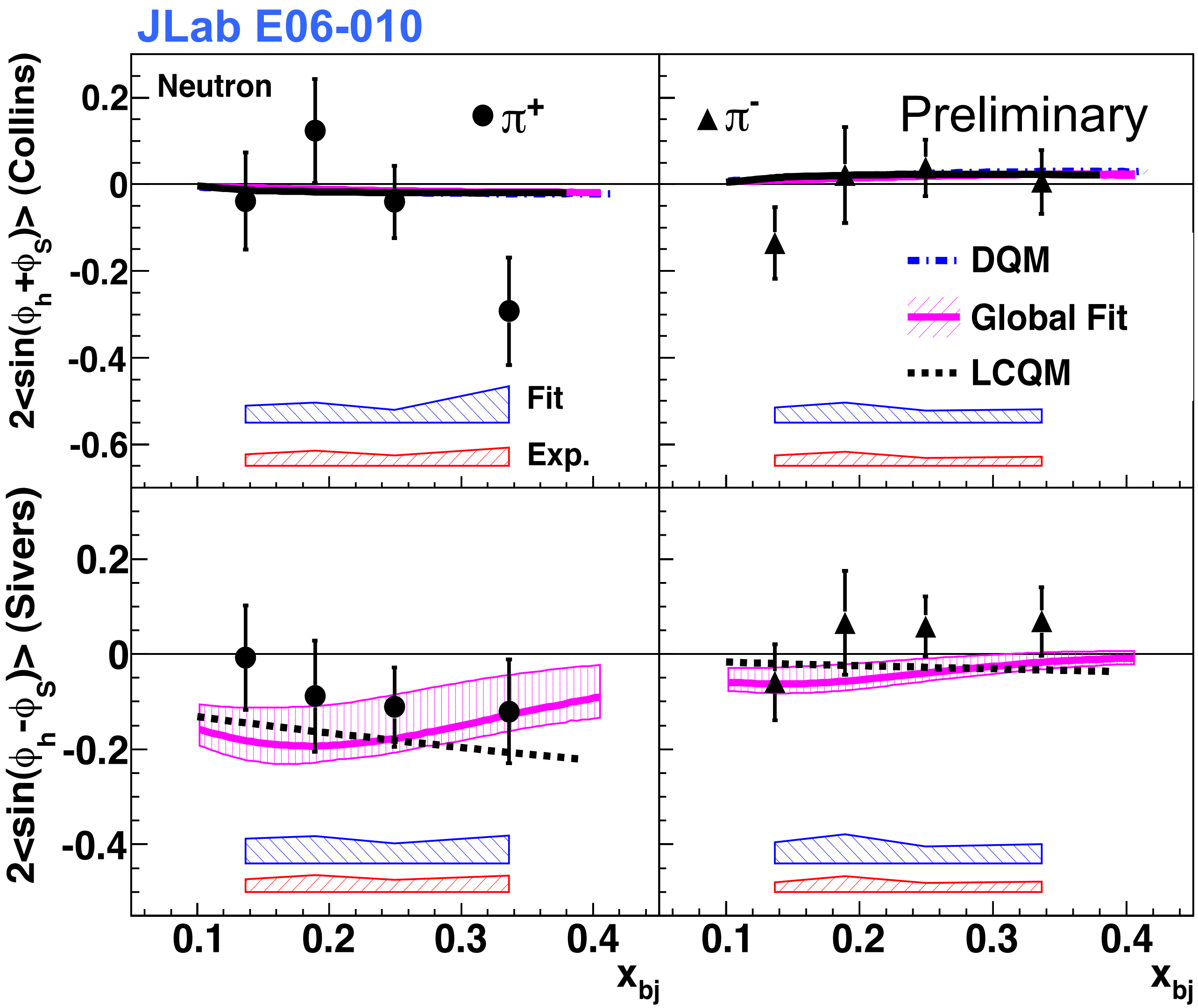


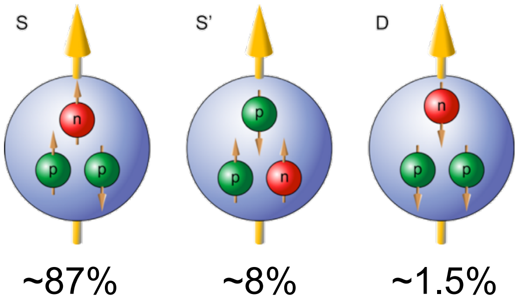
B.Musch arXiv:0907.2381
B.Pasquini et al, arXiv:0910.1677

Worm gear TMDs are unique (no analog in GPDs)

^{3}He Target Single-Spin Asymmetry in SIDIS

$$^3\mathrm{He}^{\uparrow}(e, e' h), \quad h = \pi^+, \pi^-$$





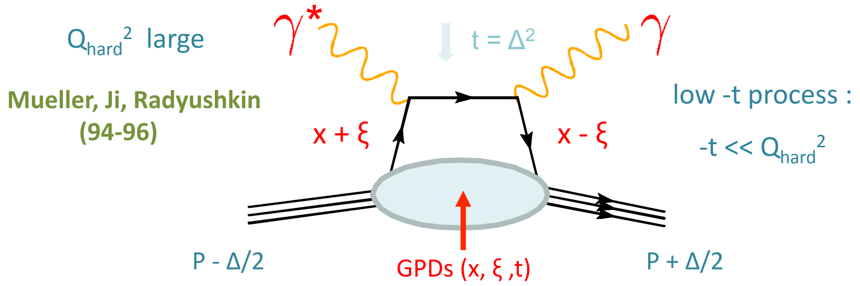
To extract information on neutron, one would assume :

$$^3\mathrm{He}^{\uparrow} = 0.865 \cdot \mathrm{n}^{\uparrow} - 2 \times 0.028 \cdot \mathrm{p}^{\uparrow}$$

Collins asymmetries for neutron are not large, except at x=0.34

Sivers agree with global fit, and light-cone quark model.

Deeply Virtual Compton Scattering



$\xi = x_B/(2-x_B)$ $k=-t/4M^2$

The DVCS amplitude is expressed in terms of Compton Form Factors (CFF) at LO:

$$\mathcal{H}(\xi,t) = \sum_q e_q^2 \left\{ i\pi \left[H^q(\xi,\xi,t) - H^q(-\xi,\xi,t)\right] + \mathcal{P}\int_{-1}^{+1} dx \left[\frac{1}{\xi - x} - \frac{1}{\xi + x}\right] H^q(x,\xi,t) \right\}$$

(similarly for other GPDs)

Proton

Polarized beam, unpolarized target (BSA) :

$$\boxed{\Delta\sigma_{LU} \sim \sin\phi \ \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi} \Longrightarrow Im\{\mathcal{H}_p, \widetilde{\mathcal{H}}_p, \mathcal{E}_p\}$$

Unpolarized beam, longitudinal target (lTSA) :

$$\boxed{\Delta\sigma_{UL} \sim \sin\phi \mathrm{Im}\{F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi kF_2 \widetilde{\mathcal{E}} + \ldots\}d\phi} \Longrightarrow Im\{\mathcal{H}_p, \widetilde{\mathcal{H}}_p\}$$

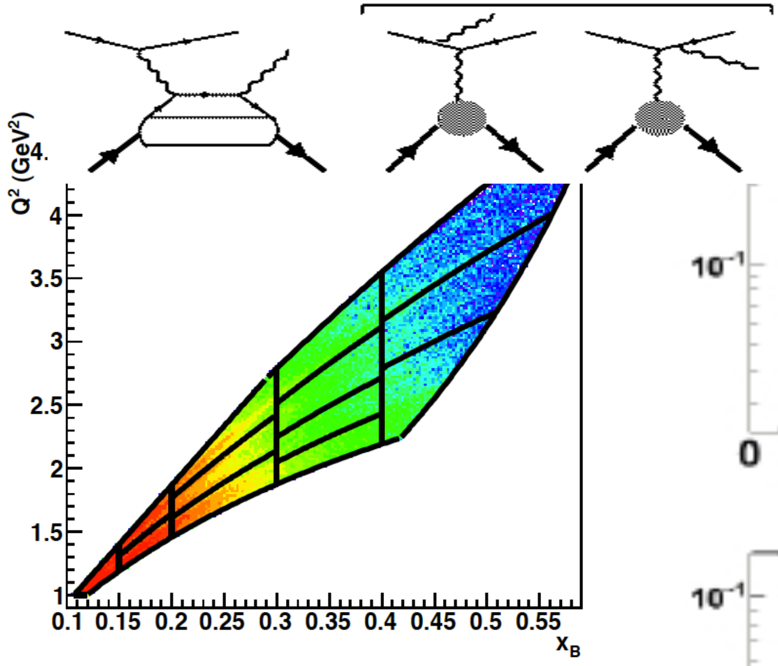
Polarized beam, longitudinal target (BlTSA) :

$$\boxed{\Delta\sigma_{LL} \sim (A + B\cos\phi)\mathrm{Re}\{F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E})\ldots\}d\phi} \Longrightarrow Re\{\mathcal{H}_p, \widetilde{\mathcal{H}}_p\}$$

Unpolarized beam, transverse target (tTSA) :

$$\boxed{\Delta\sigma_{UT} \sim \cos\phi \mathrm{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\ldots\}d\phi} \Longrightarrow Im\{\mathcal{H}_p, \mathcal{E}_p\}$$

DVCS x-sections from CLAS

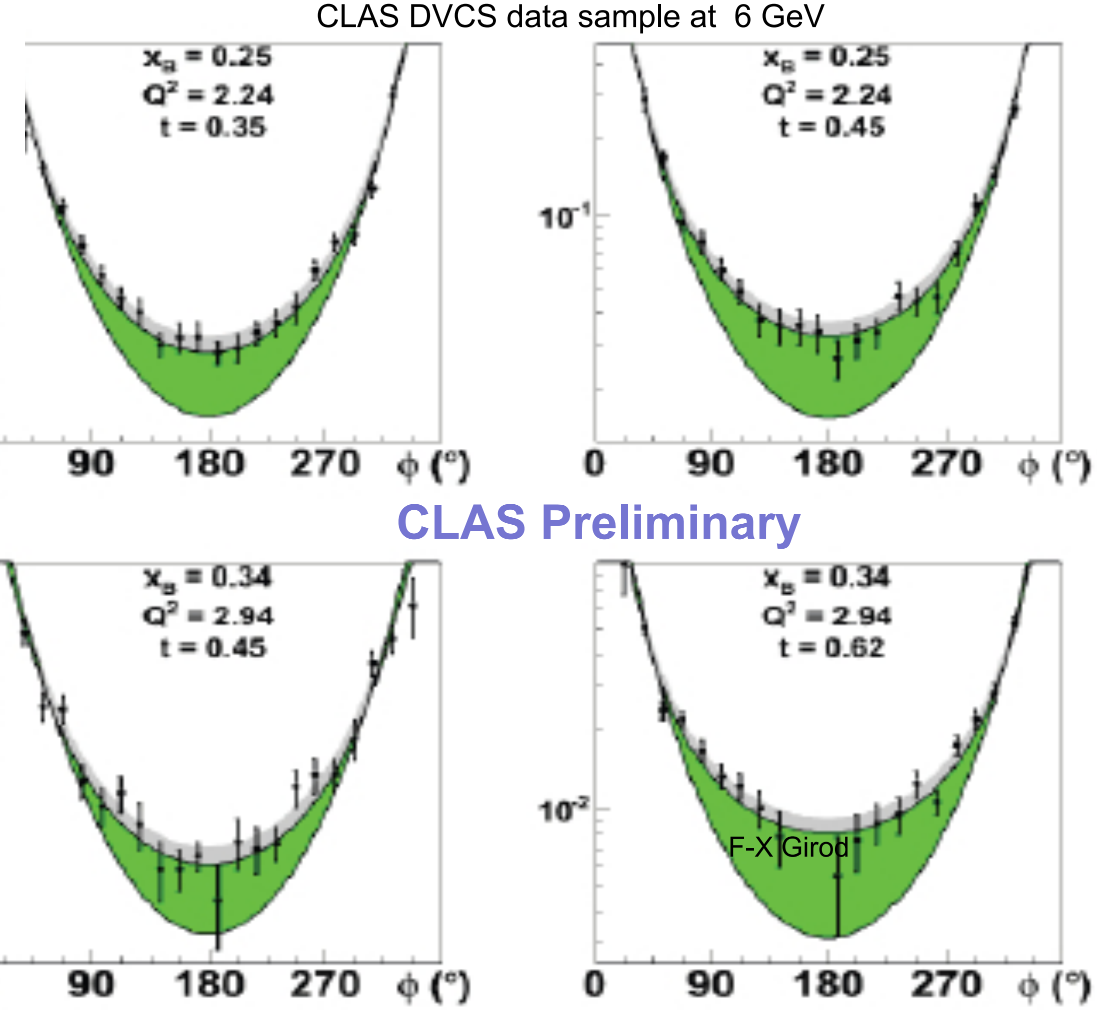


$ep_0 \rightarrow e'p_f\gamma$ $t=(p_0-p_f)^2$

Radiative corrections and π^0 contamination accounted

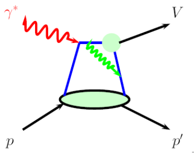
qualitatively agrees with Hall-A

CLAS DVCS data sample at 6 GeV



CLAS Preliminary

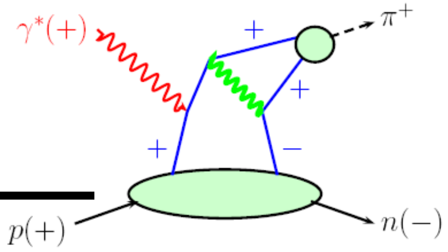
- In certain region of azimuthal angles the x-section is higher than BH calculations indicating data may be sensitive to DVCS already in JLab kinematics.



SSAs in exclusive pion production

Transverse photon matters

Ahmad,Liuti & Goldstein: arXiv:0805.3568
Gloskokov & Kroll : arXiv:0906.0460

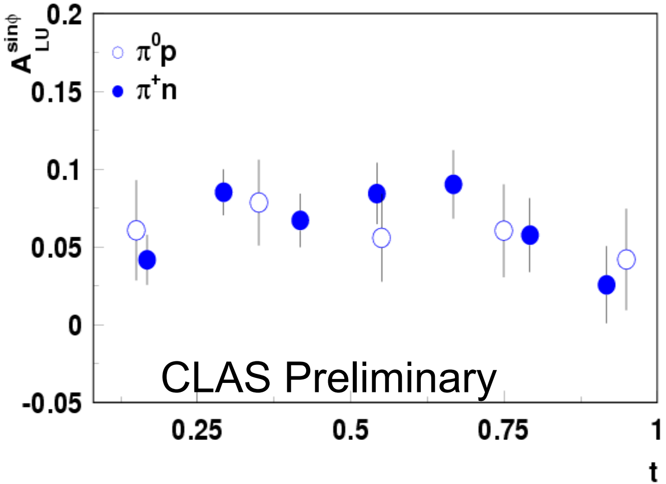


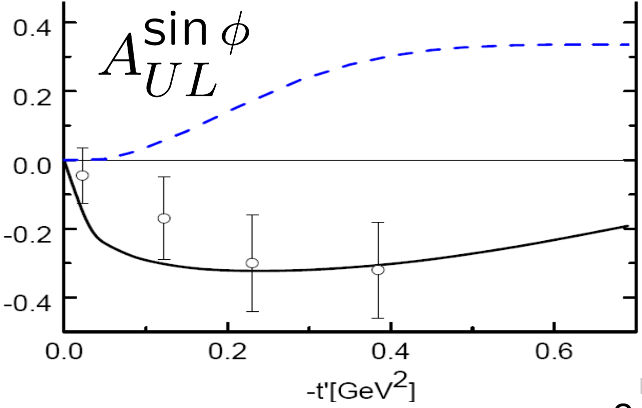
e p → e' π N

$$\mathcal{M}^{twist-3}_{0-,++} \approx e_0\sqrt{1-\xi^2}\int_{-1}^{+1} d\bar{x}\,\mathcal{H}_{0-,++}[H_T^{(3)}+\ldots]$$

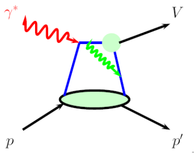
observable	dominant interf. term	amplitudes	low t' behavior
$A_{UT}^{\sin(\phi-\phi_s)}$	LL	$\mathrm{Im}[\mathcal{M}^*_{0-,0+}\mathcal{M}_{0+,0+}]$	$\propto \sqrt{-t'}$
$A_{UT}^{\sin(\phi+\phi_s)}$	TT	$\mathrm{Im}[\mathcal{M}^*_{0-,++}\mathcal{M}_{0+,++}]$	$\propto \sqrt{-t'}$
$A_{UT}^{\sin(3\phi-\phi_s)}$	TT	$\mathrm{Im}[\mathcal{M}^*_{0-,-+}\mathcal{M}_{0+,-+}]$	$\propto (-t')^{(3/2)}$
$A_{UT}^{\sin\phi_s}$	LT	$\mathrm{Im}[\mathcal{M}^*_{0-,++}\mathcal{M}_{0+,0+}]$	const.
$A_{UL}^{\sin\phi}$	LT	$\mathrm{Im}[\mathcal{M}^*_{0-,++}\mathcal{M}_{0-,0+}]$	$\propto \sqrt{-t'}$
$A_{LU}^{\sin\phi}$	LT	$\mathrm{Im}[\mathcal{M}^*_{0-,++}\mathcal{M}_{0-,0+}]$	$\propto \sqrt{-t'}$
$A_{LL}^{\cos\phi}$	LT	$\mathrm{Re}[\mathcal{M}^*_{0-,++}\mathcal{M}_{0-,0+}]$	$\propto \sqrt{-t'}$

$$A_{LU}^{\sin\phi}/A_{UL}^{\sin\phi} \approx \sqrt{(1-\epsilon)/(1+\epsilon)}$$





- HT SSAs are expected to be very significant
- Wider coverage (CLAS12,EIC) would allow measurements of Q^2 dependence of HT SSAs

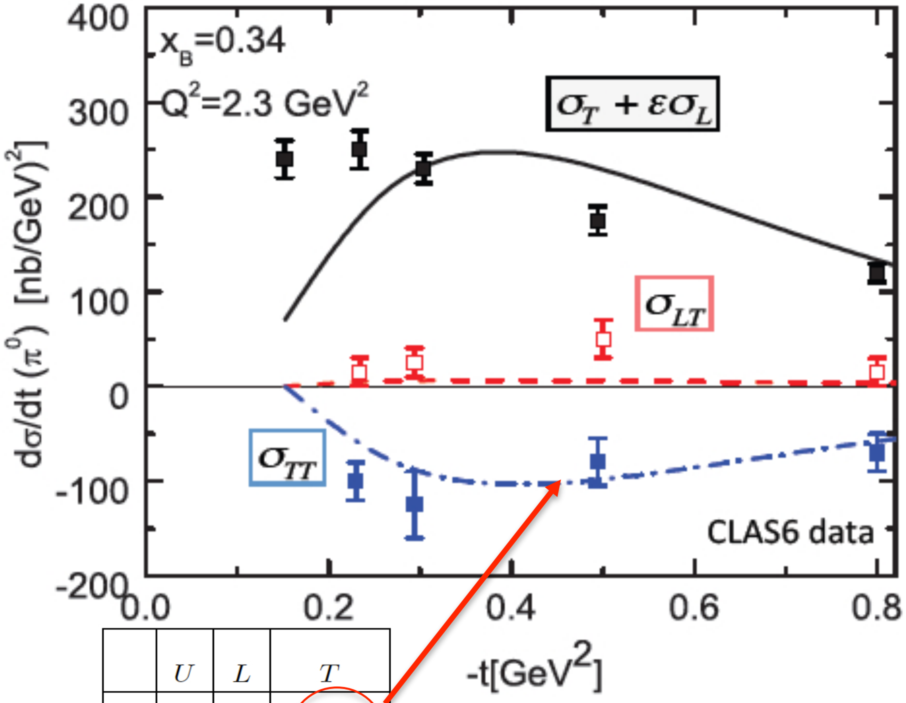


Exclusive π^0 production

Recent progress with GPD-based description

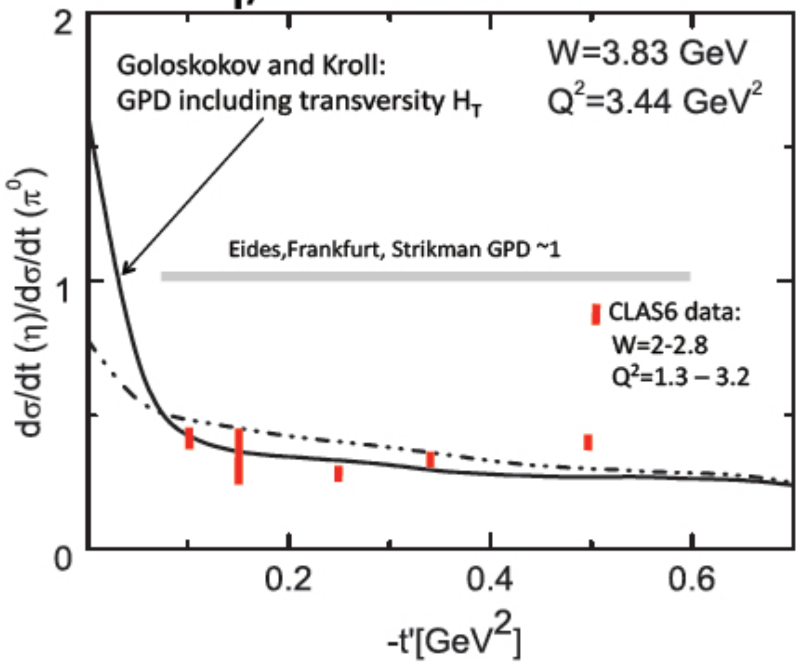
- Goloskokov&Kroll , Goldstein&Liuti . Include ***transversity* GPDs** H_T and $\mathcal{E}_T = 2\tilde{H}_T + E_T$ Dominate in CLAS kinematics. Successfully described data.

Structure Functions

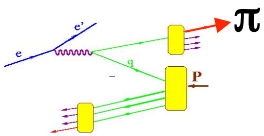


	U	L	T
U	H		$\mathcal{E}_T$
L		$\tilde{H}$	
T	E		H_T,$\tilde{H}_T$

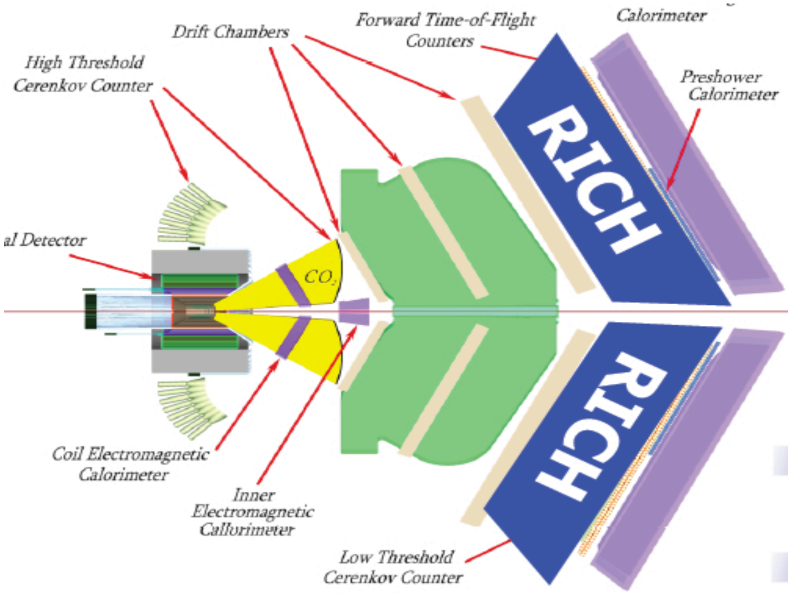
η/π^0 Ratio

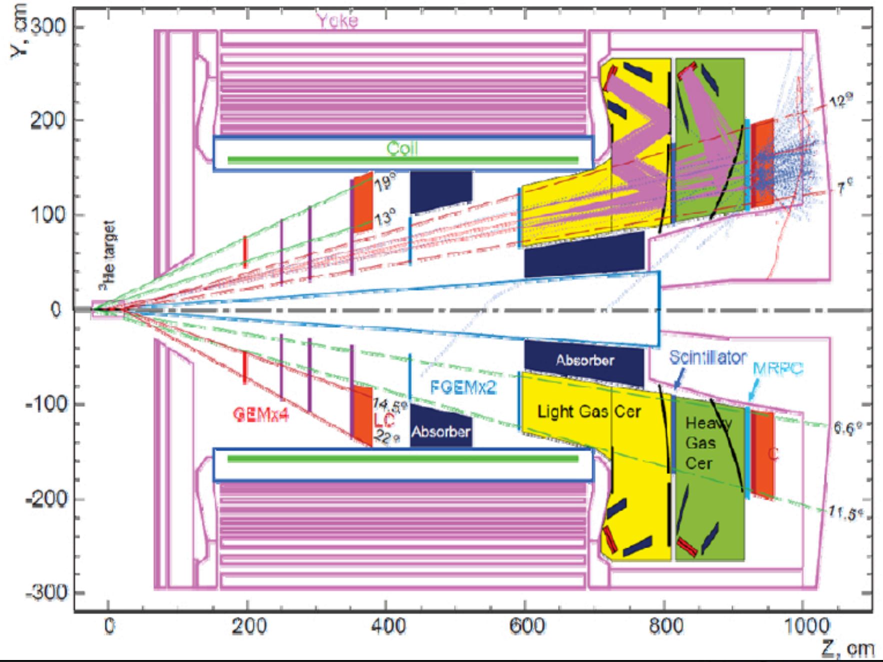


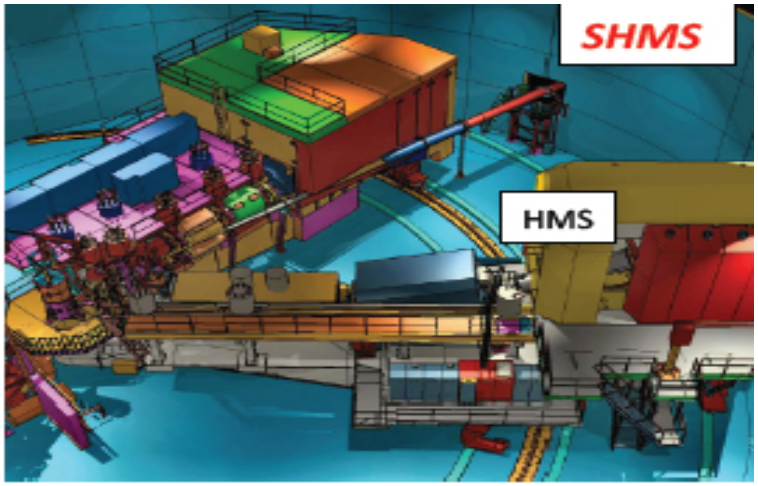
Goloskokov&Kroll
H_T and $\bar{E}_T$ dominate

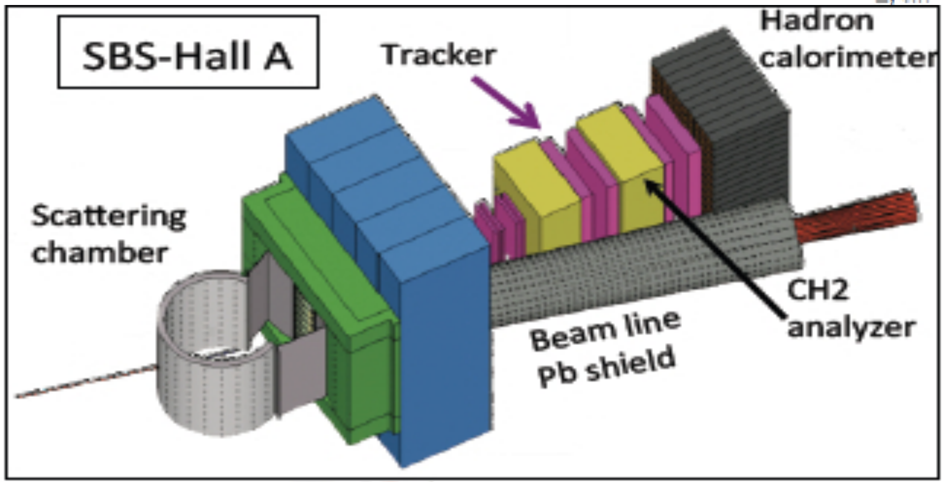


SIDIS at JLab12







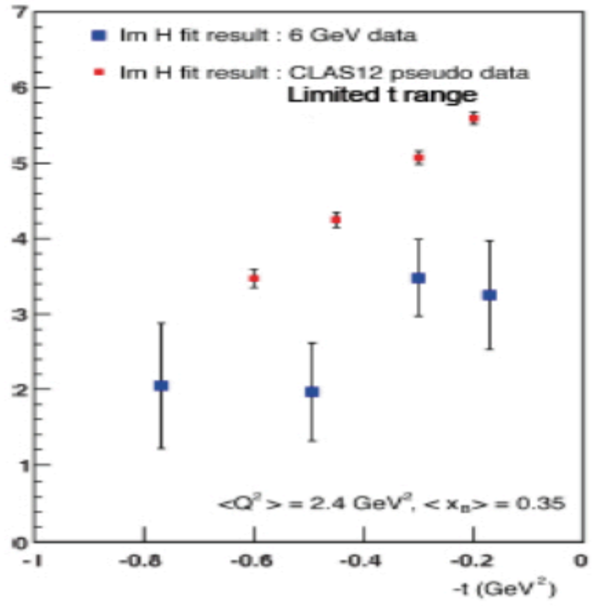


GPDs in DVCS experiments at JLab12

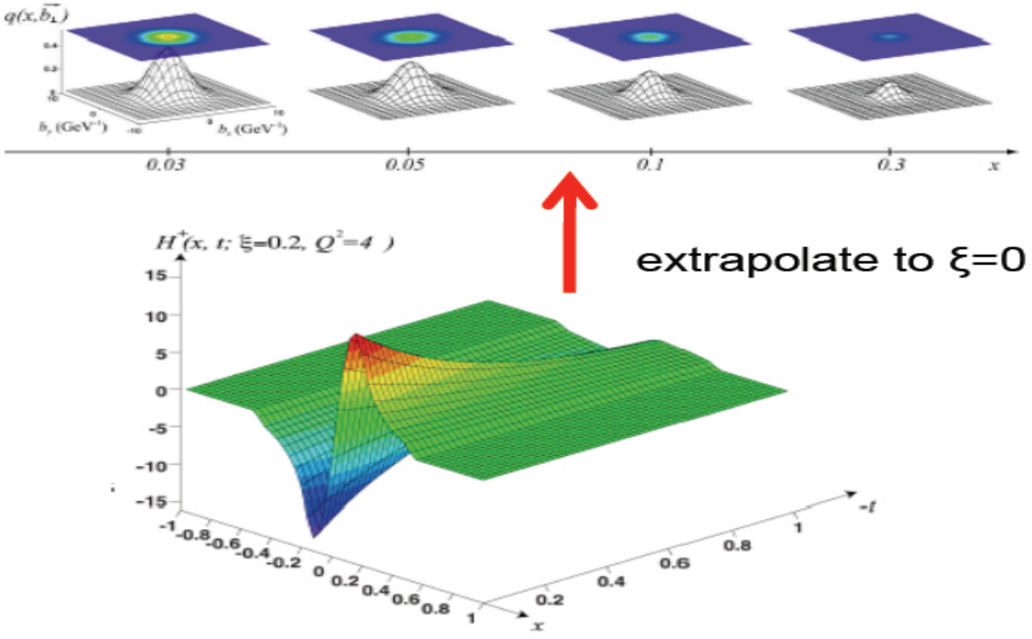
Nucleon polarization	Sensitivity to GPDs	
UP	$H, \tilde{H}, E$	E12-06-114 : γ, π^0 (A) proton E12-06-119 : γ, π^0 (B) proton E12-11-003: γ, π^0 (B) neutron
LP	$\tilde{H}, H, E$	E12-06-119 : γ, π^0 (NH_3) (B) proton
TP	E, H	LOI12-11-105 : γ, π^0 (HD) (B) proton

E12-06-119

GPD H only contribution



$$q(x,\vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} e^{i\vec{b}_\perp\cdot\vec{\Delta}_\perp} H(x,\xi=0,-\Delta_\perp^2)$$



extrapolate to ξ=0

In general, 8 GPD quantities accessible

(Compton Form Factors)

DVCS : Anticipated Leading Twist dominance already at low Q^2

$$H_{Re} = P\int_0^1 dx\,[H(x,\xi,t) - H(-x,\xi,t)]\,C^+(x,\xi) \qquad (1)$$

$$E_{Re} = P\int_0^1 dx\,[E(x,\xi,t) - E(-x,\xi,t)]\,C^+(x,\xi) \qquad (2)$$

$$\tilde{H}_{Re} = P\int_0^1 dx\left[\tilde{H}(x,\xi,t) + \tilde{H}(-x,\xi,t)\right]C^-(x,\xi), \qquad (3)$$

$$\tilde{E}_{Re} = P\int_0^1 dx\left[\tilde{E}(x,\xi,t) + \tilde{E}(-x,\xi,t)\right]C^-(x,\xi), \qquad (4)$$

$$H_{Im} = H(\xi,\xi,t) - H(-\xi,\xi,t), \qquad (5)$$

$$E_{Im} = E(\xi,\xi,t) - E(-\xi,\xi,t), \qquad (6)$$

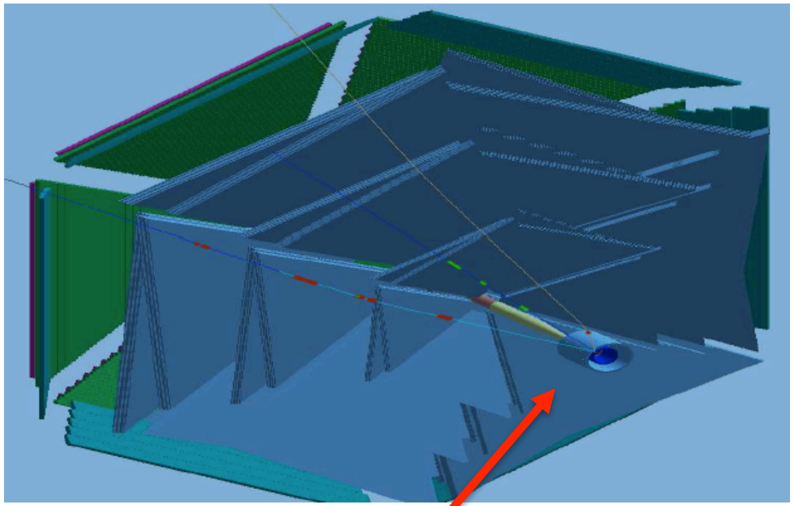
$$\tilde{H}_{Im} = \tilde{H}(\xi,\xi,t) + \tilde{H}(-\xi,\xi,t) \quad \text{and} \qquad (7)$$

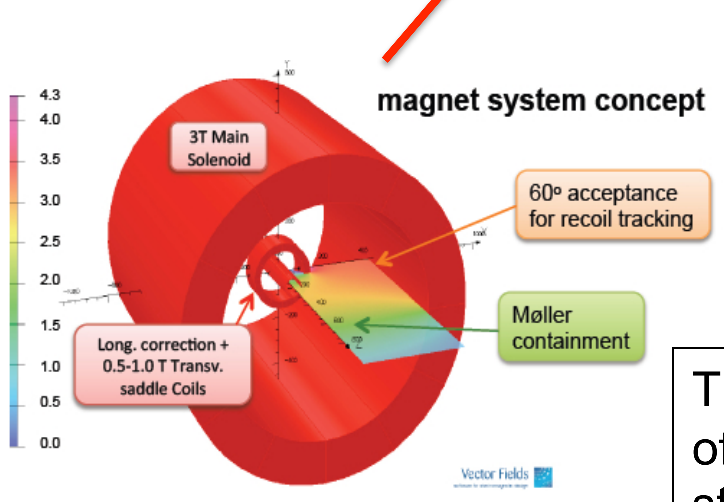
$$\tilde{E}_{Im} = \tilde{E}(\xi,\xi,t) + \tilde{E}(-\xi,\xi,t) \qquad (8)$$

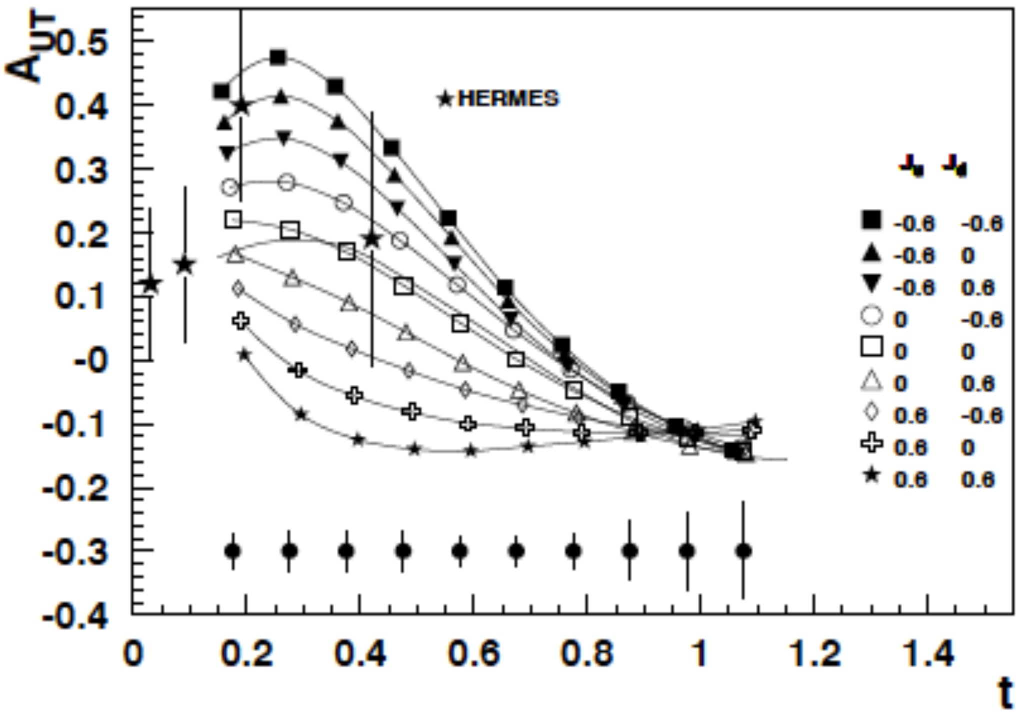
with

$$C^{\pm}(x,\xi) = \frac{1}{x-\xi} \pm \frac{1}{x+\xi}. \qquad (9)$$

DVCS with CLAS12 transverse target







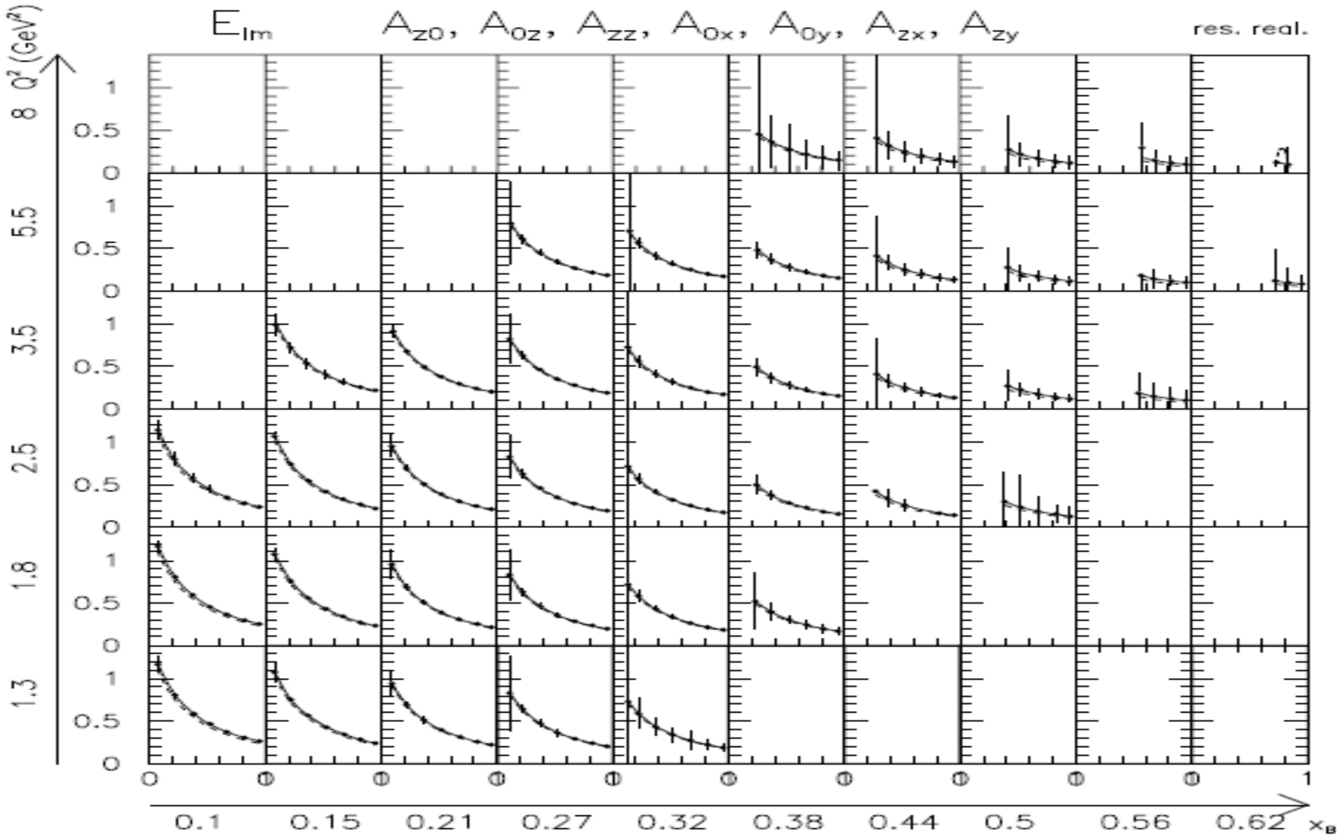
The Q^2, xB, and t dependences
of the DVCS single and double asymmetries will be studied in a wide range of kinematics.
Demonstrate capabilities to reconstruct protons

Extraction of GPDS from CLAS12 data

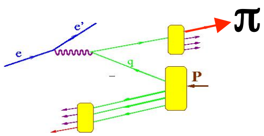
Obs=Amp(DVCS+BH) $\otimes$ CFFs

fit the BSA (A_z0) + lTSA (A_0z) + tTSA (A_0x +A_0y) + double asymmetries (A_zz+A_zx+A_zy) with "REALISTIC" resolutions

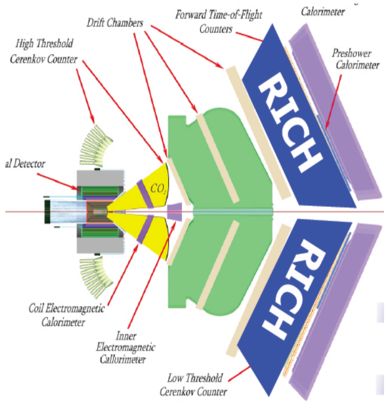
M. Guidal



The full set of Compton Form Factors (CFFs) can be reconstructed, using the full set of single and double spin asymmetries



SIDIS at JLab12



CLAS12

E12-06-112: π^+,π^-,π^0
E12-09-008: K^+, K^-,K^0

E12-07-107: π^+,π^-,π^0
E12-09-009: K^+,K^-,K^0

C12-11-111: π^+,π^-,π^0
K^+, K^-

H_2, NH_3, HD

Proton

Quark spin polarization

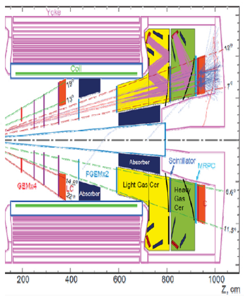
Nucleon polarization

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 $h_{1T}^\perp$

Hall C | Hall A

E12-09-017: π^+,π^-, K^+,K^-
C12-11-102: π^0

HMS
SHMS



C12-11-108: π^+,π^-

Solid

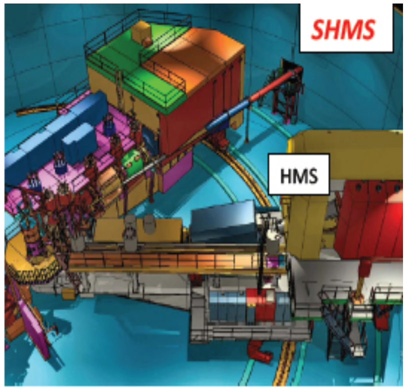
H_2 | NH_3

CLAS12

E09-008: π^+,π^-,π^0
K^+, K^-,K^0

E07-107: π^+,π^-,π^0
E09-009: K^+,K^-,K^0

D_2, ND_3



D_2

Quark spin polarization

Nucleon polarization

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 $h_{1T}^\perp$

Hall C

E12-09-017: π^+,π^-, K^+,K^-
C12-11-102: π^0

HMS
SHMS

D_2

^{3}He

Quark spin polarization

Nucleon polarization

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 $h_{1T}^\perp$

Hall A

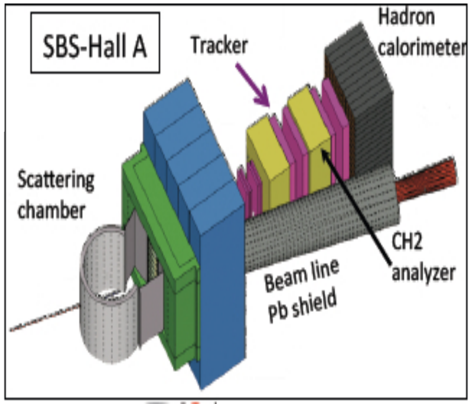
E12-07-007: π^+, π^-

Solid

E10-006: π^+,π^-
E12-09-018: π^+,π^- , K^+,K^-

Solid
SBS

^{3}He

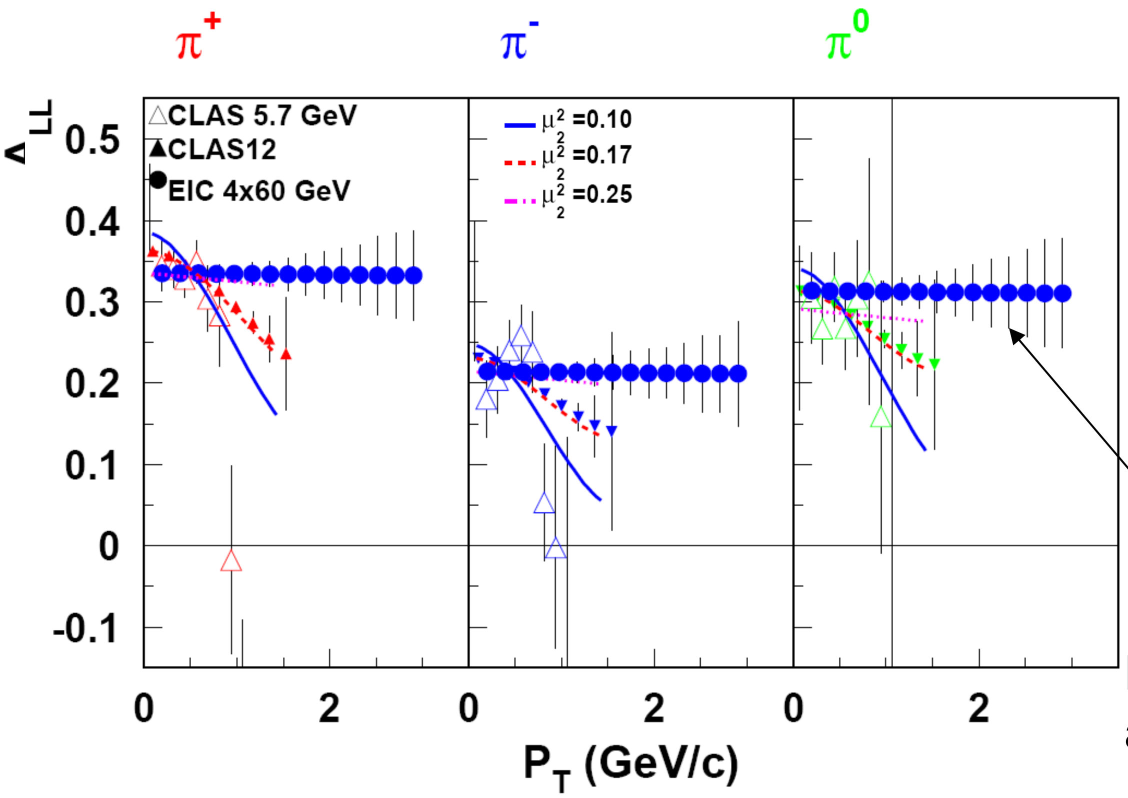


A_1 P_T-dependence in SIDIS (CLAS12)

$$A_1(\pi) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)} \; e^{-z^2 P_T^2 \frac{(\mu_0^2-\mu_2^2)}{(\mu_D^2+z^2\mu_0^2)(\mu_D^2+z^2\mu_2^2)}}$$

M.Anselmino et al

hep-ph/0608048



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

$$g_1^q(x,k_T) = g_1(x)\frac{1}{\pi\mu_2^2}\exp\left(-\frac{k_T^2}{\mu_2^2}\right)$$

$$D_1^q(z,p_T) = D_1(z)\frac{1}{\pi\mu_D^2}\exp\left(-\frac{p_T^2}{\mu_D^2}\right)$$

μ_0^2=0.25GeV^2

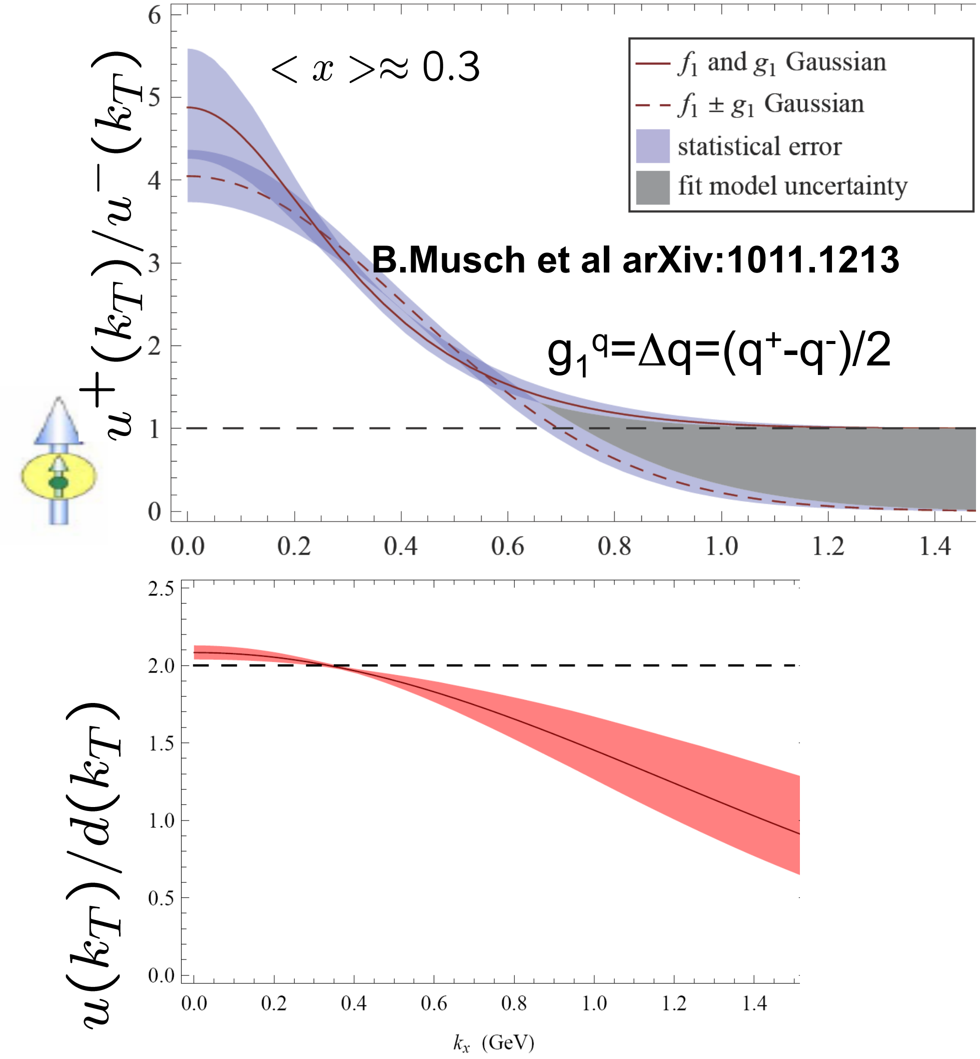
μ_D^2=0.2GeV^2

Perturbative limit calculations available for $g_1^q(x,k_T), f_1(x,k_T)$:

J.Zhou, F.Yuan, Z Liang: arXiv:0909.2238

- **A_{LL} (π) sensitive to difference in k_T distributions for f_1 and g_1**
- **Wide range in P_T allows studies of transition from TMD to perturbative approach**

Quark distributions at large k_T: lattice



B.Musch et al arXiv:1011.1213

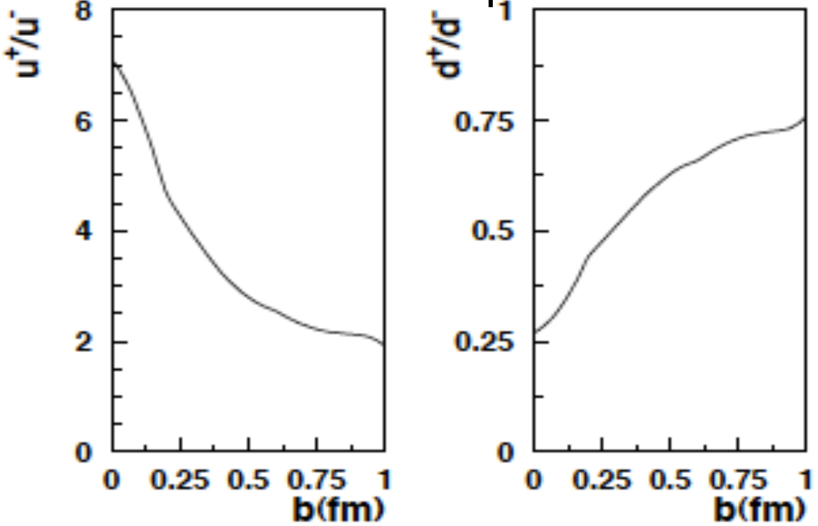
$g_1^q=\Delta q=(q^+-q^-)/2$

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

$$g_1^q(x,k_T) = g_1(x)\frac{1}{\pi\mu_2^2}\exp\left(-\frac{k_T^2}{\mu_2^2}\right)$$

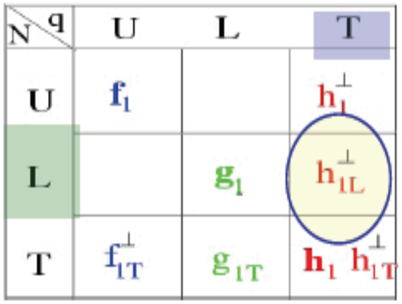
Higher probability to find a quark anti-aligned with proton spin at large k_T and b_T

B.Pasquini et al



Significant correlations of spin and transverse degrees of freedom predicted

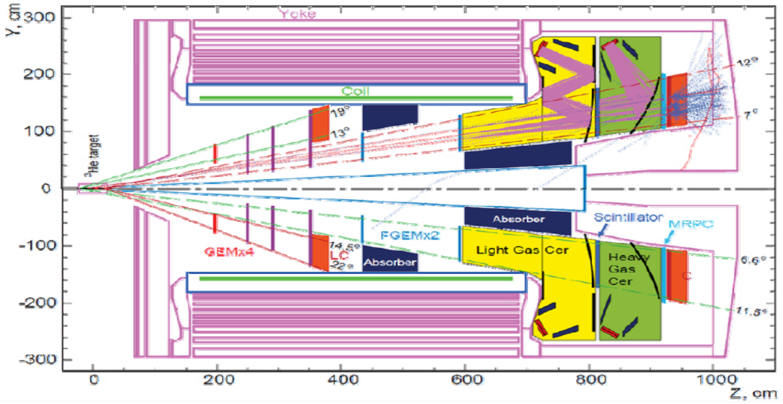
SOLID A_{UL} on ^{3}He

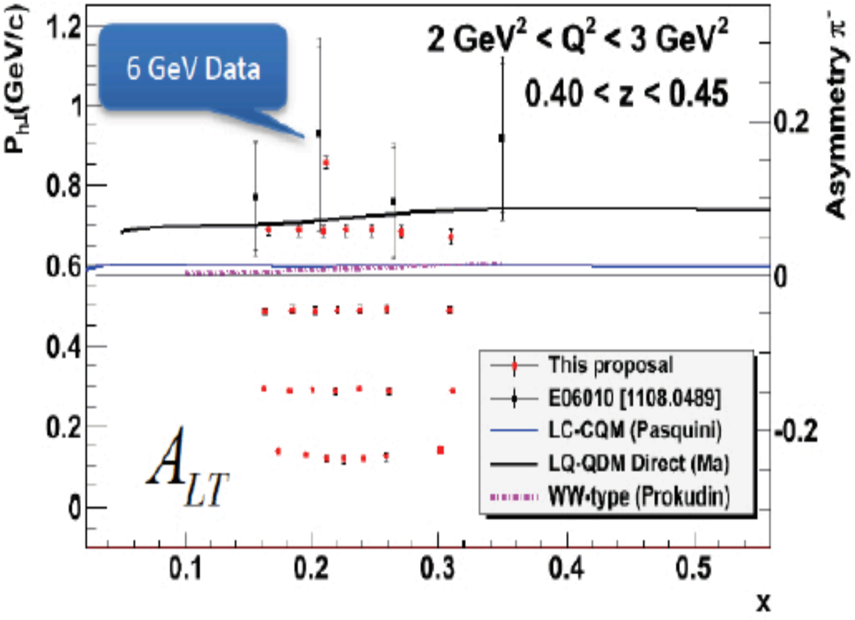


N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

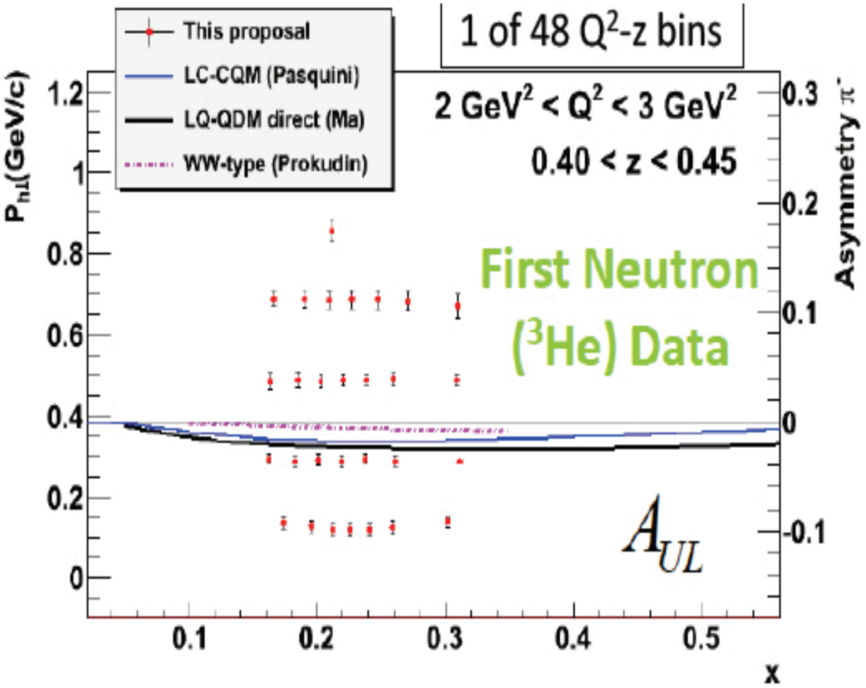
E12-11-007

$e^3He \to e\pi^- X$





6 GeV Data



1 of 48 Q^2-z bins

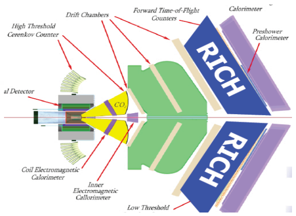
First Neutron (^{3}He) Data

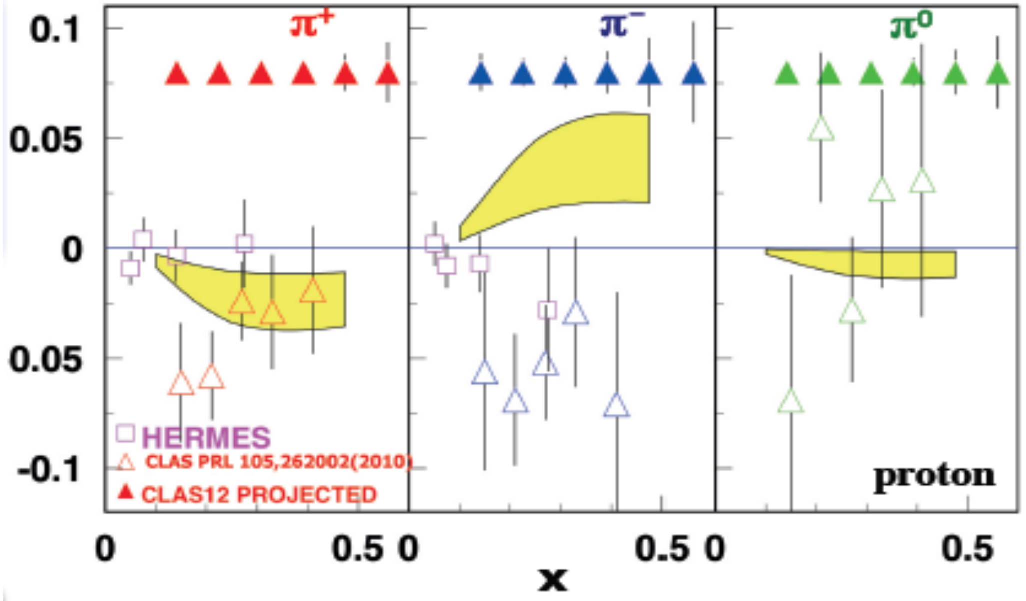
E12-07-107: Studies of Spin-Orbit Correlations with Longitudinally Polarized Target

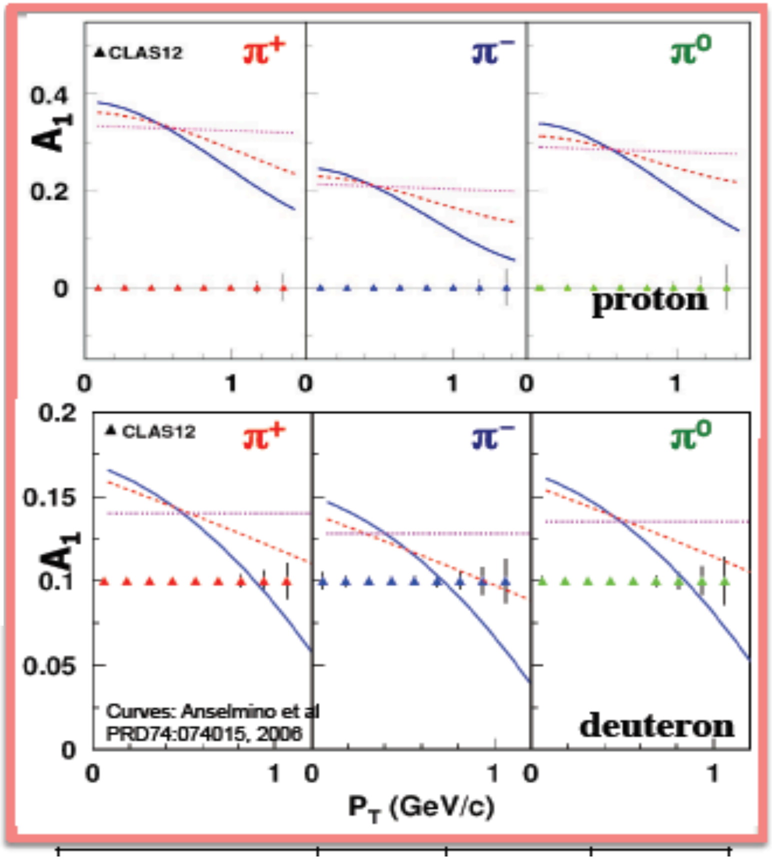
N \ q	U	L	T
L		g_{1L}	$h_{1L}^{\perp}$

$$\frac{d\sigma}{dxdyd\phi_S d\phi_h dP_{h\perp}^2} \propto S_L\left[\sqrt{2\epsilon(1+\epsilon)}sin\phi_h \overset{h.t.}{F_{UL}^{sin\phi_h}} + \epsilon sin(2\phi_h)\overset{h_{1L}^{\perp}\otimes H_1^{\perp}}{F_{UL}^{sin(2\phi_h)}}\right]$$

$$+S_L\lambda_e\left[\sqrt{1-\epsilon^2}\underset{g_{1L}\otimes D_1}{F_{LL}} + \sqrt{2\epsilon(1-\epsilon)}cos(\phi_h)\underset{h.t.}{F_{LL}^{cos(\phi_h)}}\right]$$

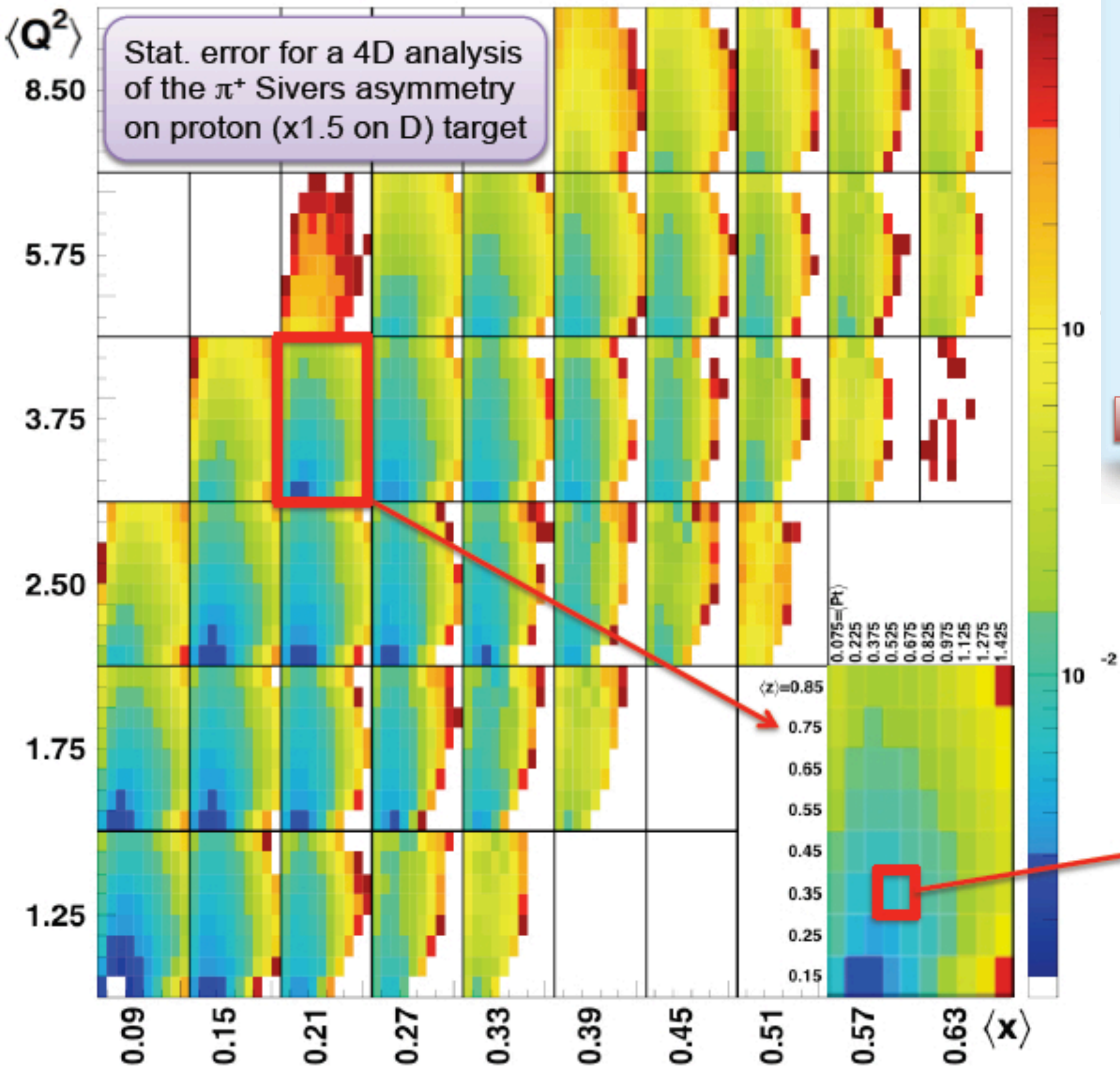




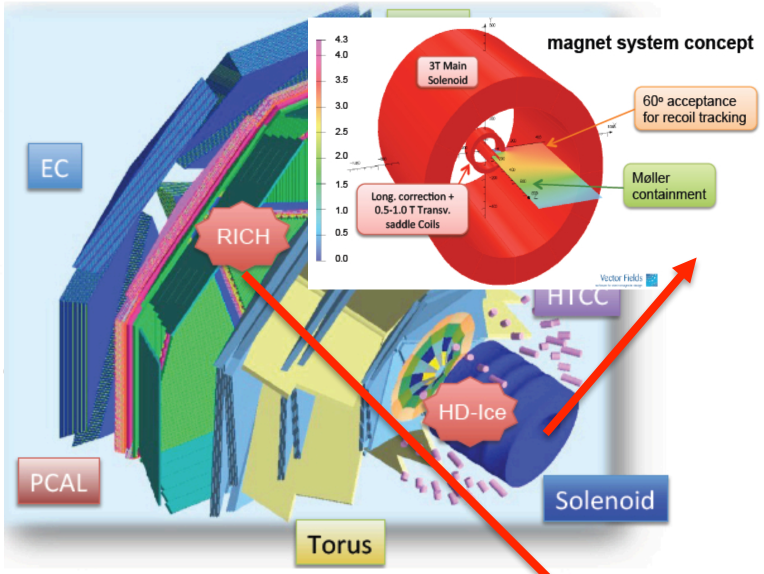


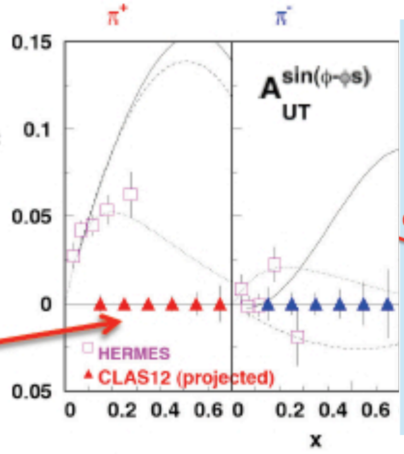
- A_1 P_T-dependence provides access to helicity dependence of k_T-distributions of quarks
- p & d data required for P_T-dependence flavor decomposition

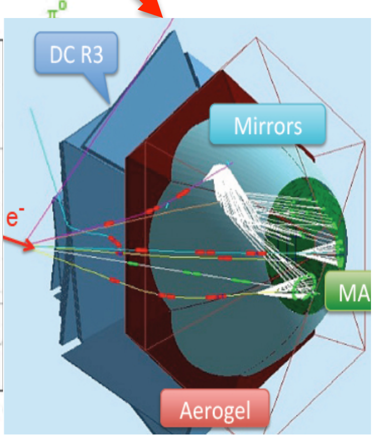
CLAS12 A_{UT} with transverse proton target



Stat. error for a 4D analysis of the π^+ Sivers asymmetry on proton (x1.5 on D) target







Curves from hep-ph/0507266 and hep-ph/0507181

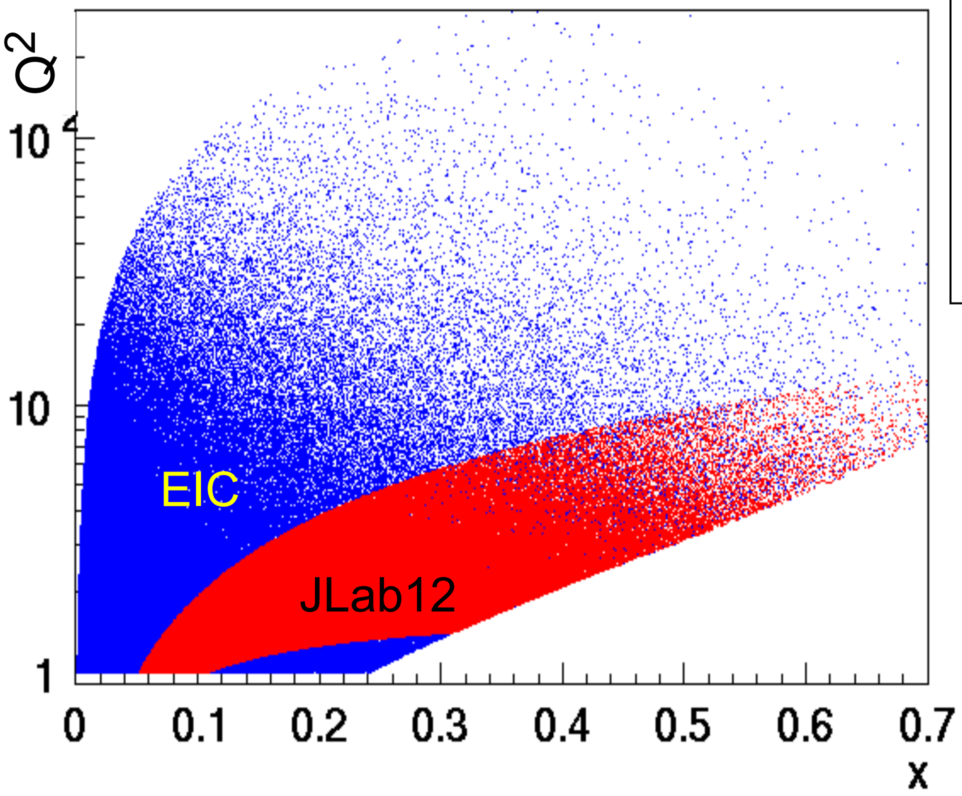
From JLab12 to EIC

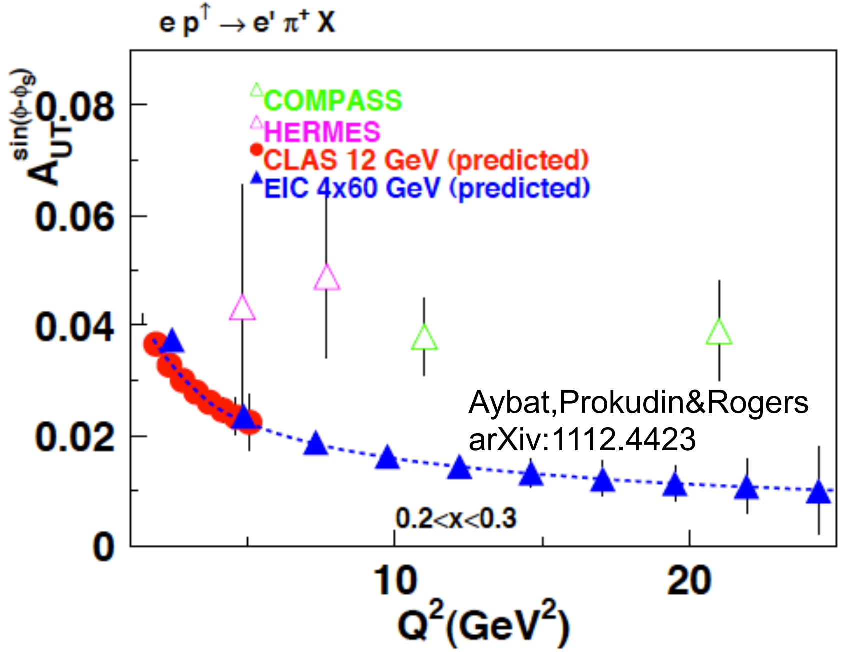
JLab@12GeV (25/50/75)

→$0.1<x_B<0.7$: valence quarks

EIC √s = 140, 50, 15 GeV

→$10^{-4}<x_B<0.3$: gluons and quarks, higher P_T and Q^2.

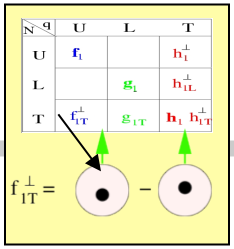


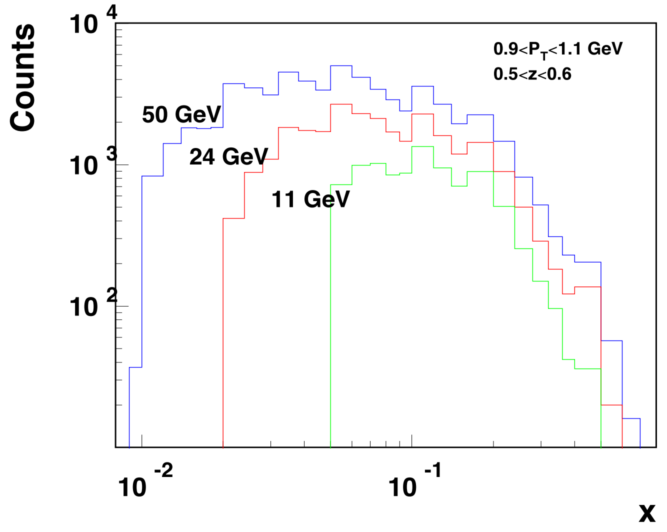


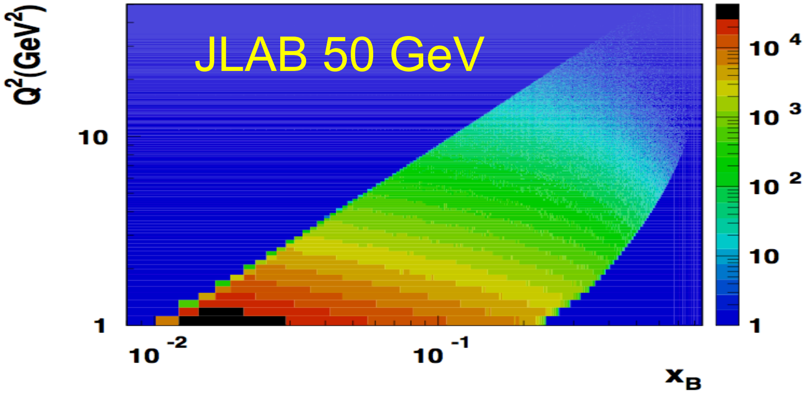
$$A_{UT}^{\sin(\phi-\phi_S)} = \frac{\sum_q e_q^2 f_{1T}^{\perp q} D_1^q}{\sum_q e_q^2 f_1^q D_1^q}$$

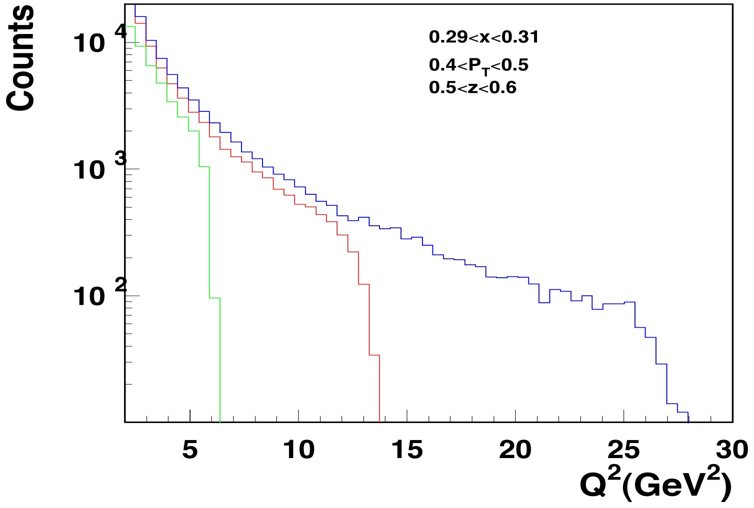
- Study of high **x** domain requires high luminosity, low **x** higher energies
- Wide range in Q^2 is crucial to study the evolution
- Overlap of EIC and JLab12 in the valence region will be crucial for the TMD program

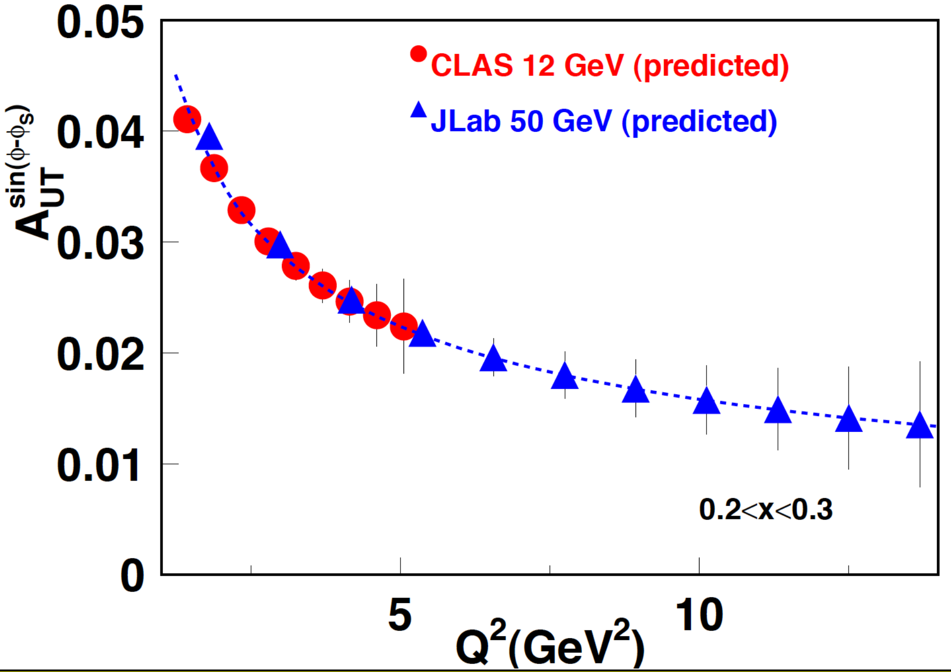
$ep \rightarrow e'\pi^+X$ From JLab12 to JLab50









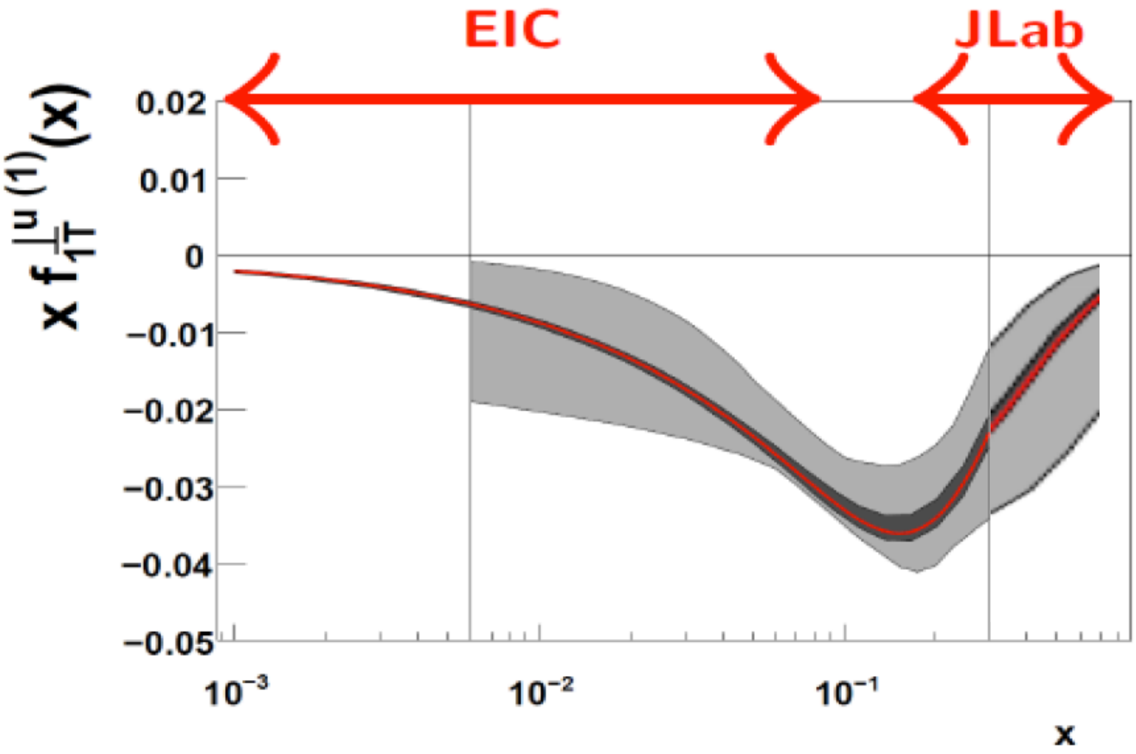


For a given lumi (30min of runtime) and given bin in hadron z and P_T, higher energy provides higher counts and wider coverage in Q^2, allowing studies of Q^2 evolution of 3D partonic distributions in a wide Q^2 range.

Extracting Sivers function from asymmetries

$$A_{UT}^{\sin(\phi-\phi_S)} = \frac{\sum_q e_q^2 f_{1T}^{\perp q} D_1^q}{\sum_q e_q^2 f_1^q D_1^q}$$

EIC with energy setting of √s = 45 GeV and an integrated lumi of 4 fb−1



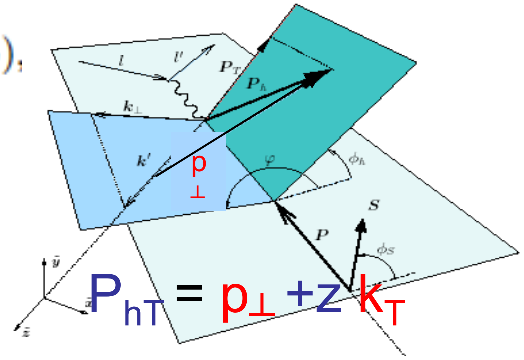
Extraction based on Gaussian Sivers, generated and then extracted with assumption of the same shape as used in generation (unclear systematics)

•It is crucial to have a well defined, model-independent procedure for extraction of k_T-dependent PDFs.

SIDIS with Bessel weighting

$$F_{UU,T} = x \sum_a e_a^2 \int d^2p_T\, d^2k_T\, \delta^{(2)}(p_T - k_T - P_{h\perp}/z)\, w(p_T, k_T)\, f^a(x, p_T^2)\, D^a(z, k_T^2),$$

$$\delta^{(2)}(zp_T + K_T - P_{h\perp}) = \int \frac{d^2 b_T}{(2\pi)^2}\, e^{ib_T(zp_T + K_T - P_{h\perp})}$$



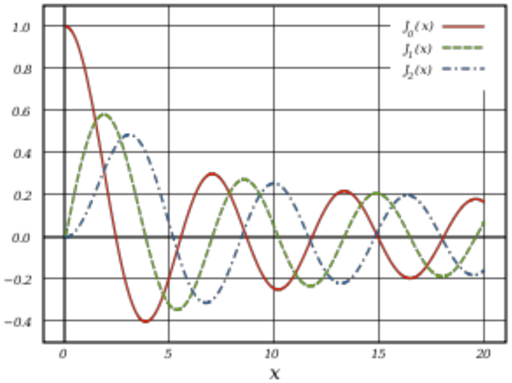
$P_{hT} = p_\perp + z\, k_T$

$$F_{UU,T} = x_B \sum_a e_a^2 \int \frac{d|b_T|}{(2\pi)} |b_T|\, J_0(|b_T|\,|P_{h\perp}|)\; \tilde{f}_1(x, z^2 b_T^2)\; \tilde{D}_1(z, b_T^2)$$

$$\int_0^\infty d|P_{h\perp}|\,|P_{h\perp}|\, J_n(|P_{h\perp}|\,|b_T|)\, J_n(|P_{h\perp}|\,\mathcal{B}_T) = \frac{1}{\mathcal{B}_T}\delta(|b_T| - \mathcal{B}_T)$$

$$\tilde{f}_1^q(x, z^2 b_T^2)\, \tilde{D}_1^{q\to\pi}(z, b_T^2)$$

$$\tilde{f}(x, b_T^2) \equiv \int d^2p_T\, e^{ib_T\cdot p_T}\; f(x, p_T^2) = 2\pi \int d|p_T||p_T|\; J_0(|b_T||p_T|)\; f(x, p_T^2)$$



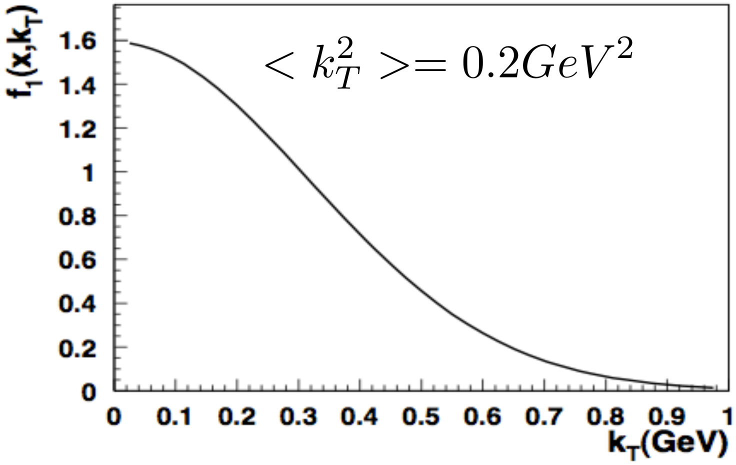
$$F_{LL} = x_B \sum_a e_a^2 \int \frac{d|b_T|}{(2\pi)} |b_T|\, J_0(|b_T|\,|P_{h\perp}|)\; \tilde{g}_{1L}(x, z^2 b_T^2)\; \tilde{D}_1(z, b_T^2)$$

- the formalism in **b_T-space** avoids convolutions
- provides a model independent way to study kinematical dependences of TMD

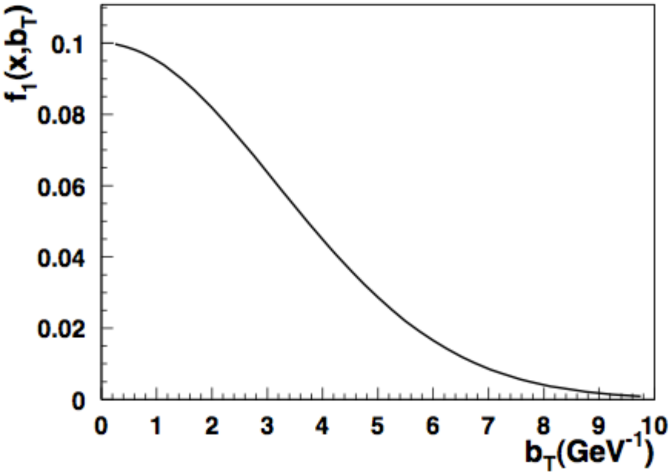
SIDIS with Bessel weighting

$$\tilde{f}(x, \boldsymbol{b}_T^2) \equiv \int d^2\boldsymbol{p}_T\, e^{i\boldsymbol{b}_T\cdot\boldsymbol{p}_T}\, f(x, \boldsymbol{p}_T^2) = 2\pi \int d|\boldsymbol{p}_T||\boldsymbol{p}_T|\; J_0(|\boldsymbol{b}_T||\boldsymbol{p}_T|)\; f(x, \boldsymbol{p}_T^2)$$

$$f_1(x, k_T) = \frac{N}{\pi < k_T^2 >} e^{-\frac{k_T^2}{<k_T^2>}}$$



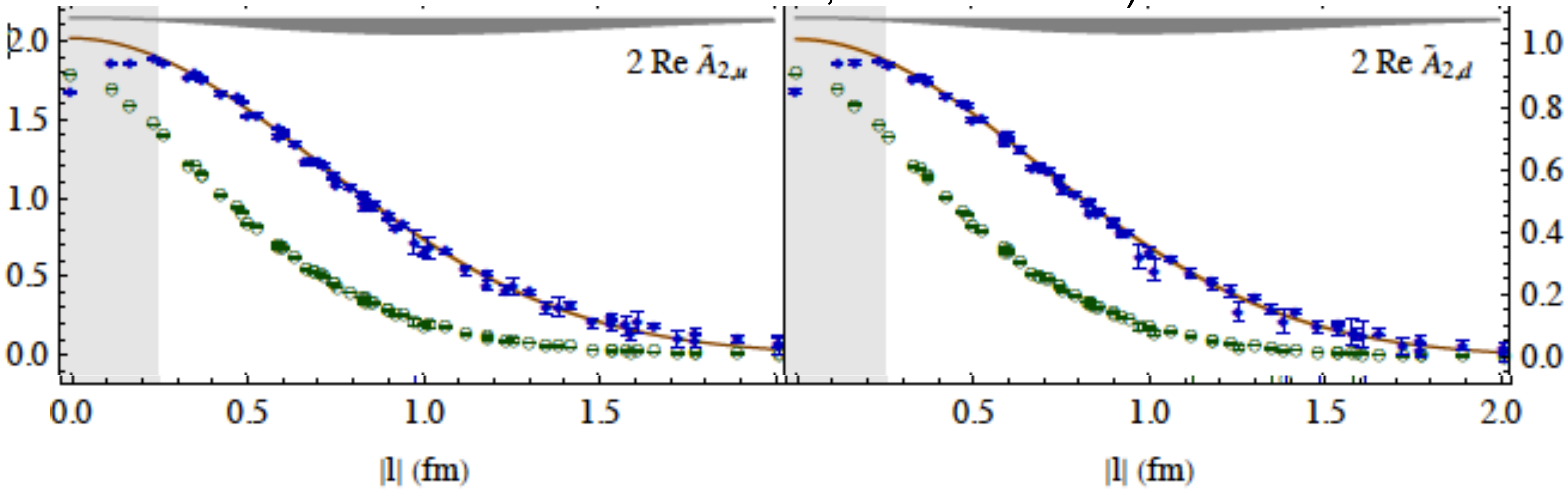
$$\tilde{f}_1(x, b_T^2) = \frac{1}{2} < k_T^2 > N e^{-\frac{<k_T^2> b_T^2}{4}}$$



- the data analysis can be performed in the **b_T-space**.

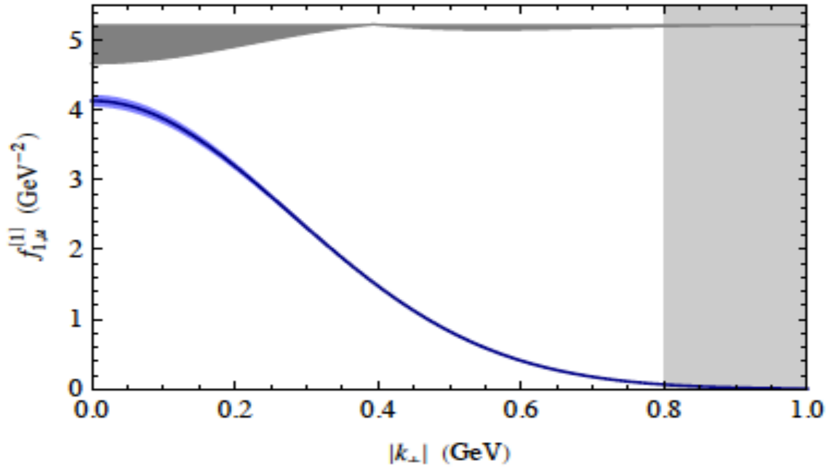
Lattice calculations and b_T-space

(PDFs in terms of Lorenz invariant amplitudes $\tilde{A}_i$
Musch et al, arXiv:1011.1213)

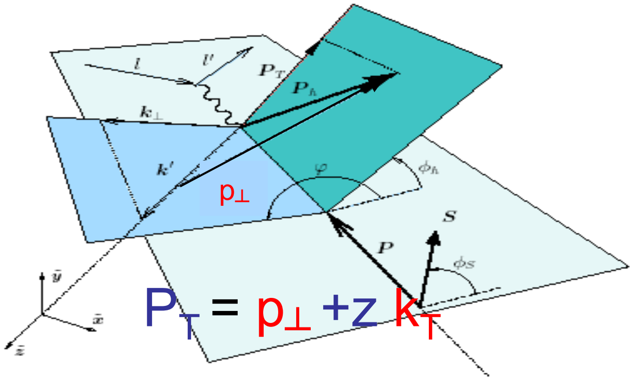


	c_2	σ_2
$\tilde{A}_{2,u}$	$2.0186 \pm 0.0063 \pm 0.0008$	$1.001 \pm 0.010 \pm 0.068$
$\tilde{A}_{2,d}$	$1.0171 \pm 0.0064 \pm 0.0005$	$0.975 \pm 0.012 \pm 0.063$

$$f_1^{[1]}(\boldsymbol{k}_\perp^2) = \frac{c_2\,\sigma_2^2}{4\pi} e^{-\frac{\boldsymbol{k}_\perp^2}{(2/\sigma_2)^2}}$$



FAST-MC for CLAS12



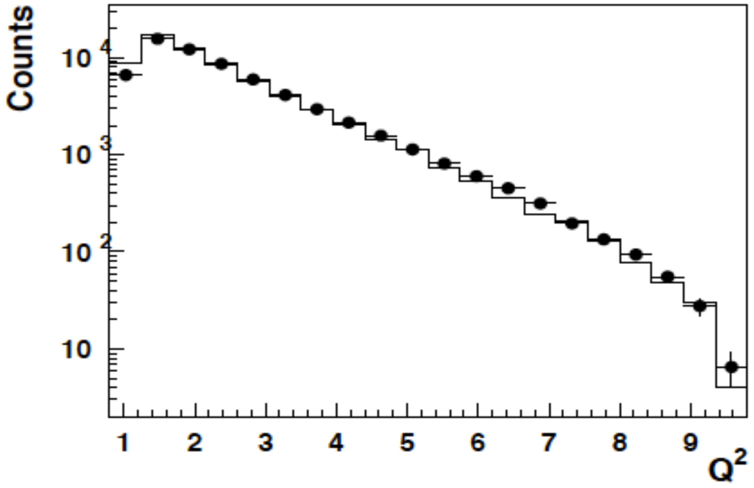
SIDIS MC in 8D $(x,y,z,\phi,\phi_S,p_T,\lambda,\pi)$

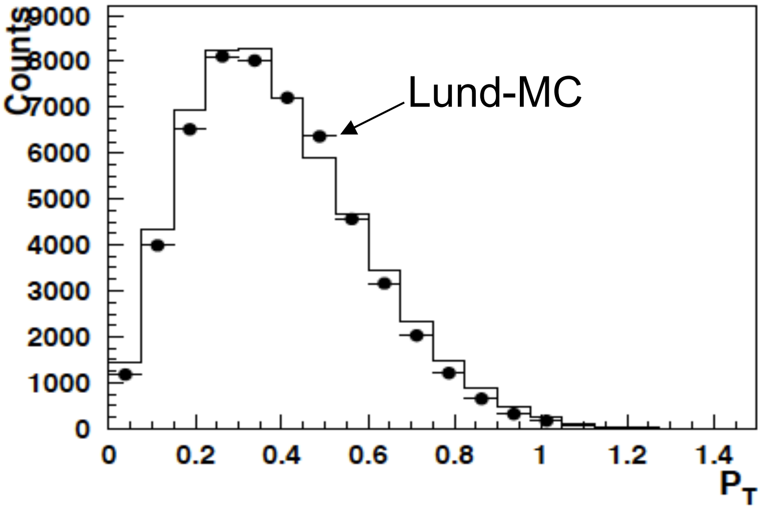
Simple model with 10% difference between f1 (0.2GeV^2) and g1 widths with a fixed width for D1 (0.14GeV^2)

$$f_q(x,k_\perp) = f_q(x)\,\frac{1}{\pi\langle k_\perp^2\rangle}\,e^{-k_\perp^2/\langle k_\perp^2\rangle}$$

CLAS12 acceptance & resolutions

Events in CLAS12





Reasonable agreement of kinematic distributions with realistic LUND simulation

BGMP: extraction of k_T-dependent PDFs

Need: project x-section onto Fourier mods in b_T-space to avoid convolution

Boer, Gamberg, Musch &Prokudin arXiv:1107.5294

$$\int_0^\infty d|P_{h\perp}|\,|P_{h\perp}|\,J_0(|P_{h\perp}||b_T|)\left[\frac{d\sigma}{dx_B\,dy\,d\phi_S\,dz_h\,d\phi_h\,|P_{h\perp}|d|P_{h\perp}|}\right]$$

$$\Downarrow$$

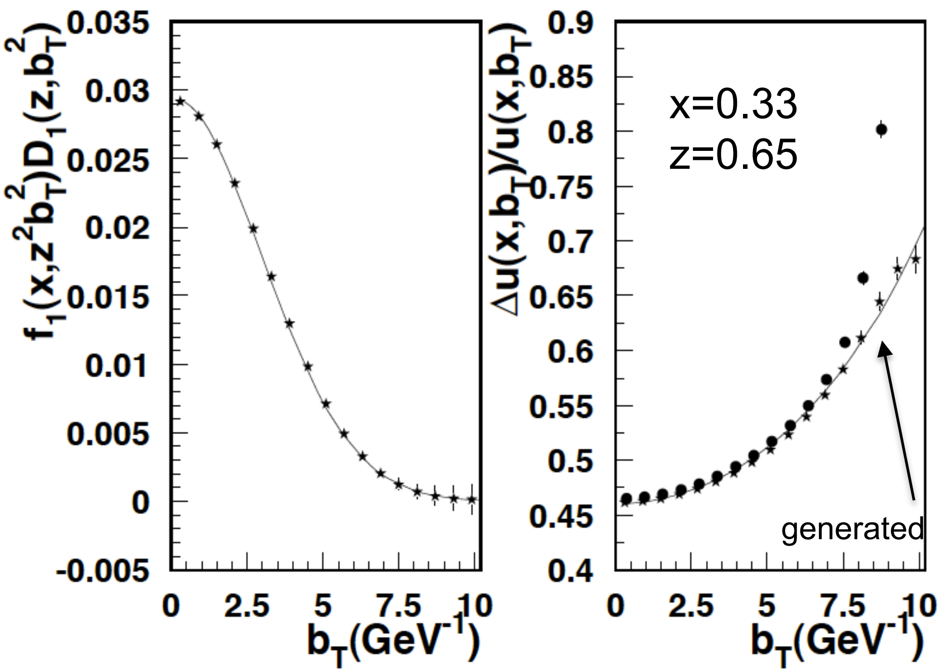
$$S_\pi^{unp\pm}(x_i,z_i,b_{Tj}) = \sum_{i=1}^{N_\pi^+/N_\pi^-} J_0(b_{Tj}P_{Ti})/\eta_i/A(x_i,y_i)$$

acceptance

$$A(x,y) = \frac{\alpha^2}{x_B y Q^2}\,\frac{y^2}{(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)$$

$$\Downarrow$$

$$\tilde{f}_1^q(x,z^2b_T^2)\,\tilde{D}_1^{q\to\pi}(z,b_T^2)$$



$$\Delta u(x,b_T)/u(x,b_T) = \frac{S_\pi^{pol+} - S_\pi^{pol-}}{S_\pi^{unp+} + S_\pi^{unp-}}$$

- the formalism in **b_T-space** avoids convolutions → easier to **perform a model independent analysis**
- provides a model independent way to study kinematical dependences of TMD
- requires wide range in hadron P_T

BGMP: extraction of k_T-dependent PDFs

Need: project x-section onto Fourier mods in b_T-space to avoid convolution

Boer, Gamberg, Musch &Prokudin arXiv:1107.5294

$$\int_0^{2\pi} d\phi_h \sin\phi_h \int_0^{\infty} d|\mathbf{P_{h\perp}}||\mathbf{P_{h\perp}}| \frac{2J_1(|\mathbf{P_{h\perp}}||\mathbf{b_T}|)}{zM_h|\mathbf{b_T}|}\left[\frac{d\sigma}{dxdydzd\phi_h|\mathbf{P_{h\perp}}|d|\mathbf{P_{h\perp}}|}\right]$$

$$\searrow$$

$$\sum_a e_a^2 \tilde{e}^a(x, z^2 b_T^2)\tilde{H}_1^{\perp(1)a}(z, b_T^2) + \ldots$$

$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = -x_B \sum_a e_a^2 \int \frac{d|b_T|}{(2\pi)}|b_T|^2 J_1(|b_T||P_{h\perp}|)\; Mz\; \tilde{f}_{1T}^{\perp(1)}(x, z^2 b_T^2)\; \tilde{D}_1(z, b_T^2)\;,$$

$$F_{LL} = x_B \sum_a e_a^2 \int \frac{d|b_T|}{(2\pi)}|b_T|\, J_0(|b_T||P_{h\perp}|)\; \tilde{g}_{1L}(x, z^2 b_T^2)\; \tilde{D}_1(z, b_T^2)\;,$$

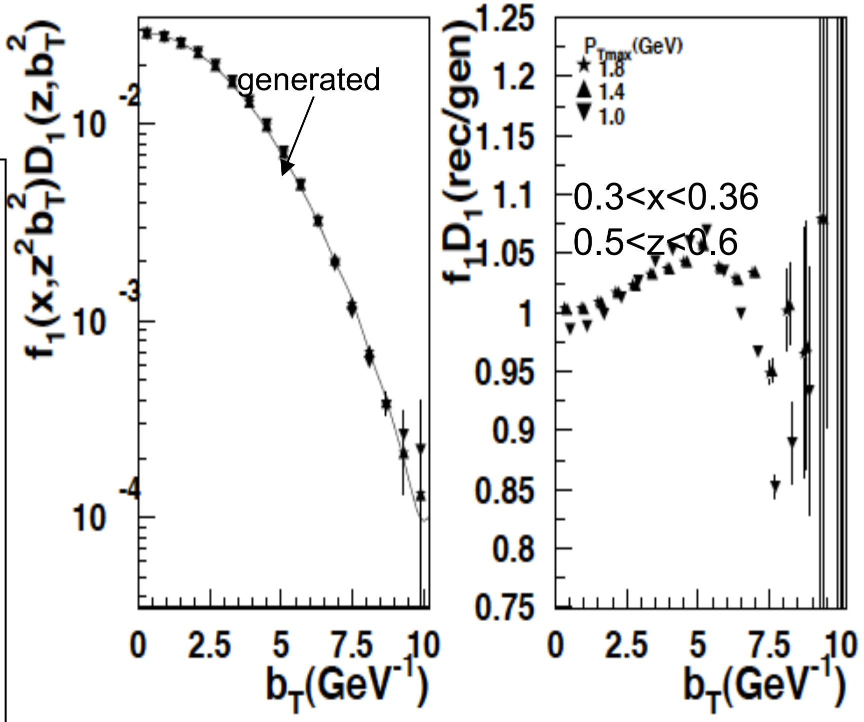
$$F_{LT}^{\cos(\phi_h-\phi_s)} = x_B \sum_a e_a^2 \int \frac{d|b_T|}{(2\pi)}|b_T|^2 J_1(|b_T||P_{h\perp}|)\; Mz\;\; \tilde{g}_{1T}^{\perp(1)}(x, z^2 b_T^2)\; \tilde{D}_1(z, b_T^2)\;,$$

$$F_{UT}^{\sin(\phi_h+\phi_S)} = x_B \sum_a e_a^2 \int \frac{d|b_T|}{(2\pi)}|b_T|^2 J_1(|b_T||P_{h\perp}|)\; M_h z\; \tilde{h}_1(x, z^2 b_T^2)\; \tilde{H}_1^{\perp(1)}(z, b_T^2)\;,$$

$$F_{UU}^{\cos(2\phi_h)} = x_B \sum_a e_a^2 \int \frac{d|b_T|}{(2\pi)}|b_T|^3 J_2(|b_T||P_{h\perp}|) M M_h z^2\; \tilde{h}_1^{\perp(1)}(x, z^2 b_T^2)\; \tilde{H}_1^{\perp(1)}(z, b_T^2)\;,$$

$$F_{UL}^{\sin(2\phi_h)} = x_B \sum_a e_a^2 \int \frac{d|b_T|}{(2\pi)}|b_T|^3 J_2(|b_T||P_{h\perp}|) M M_h z^2\; \tilde{h}_{1L}^{\perp(1)}(x, z^2 b_T^2)\; \tilde{H}_1^{\perp(1)}(z, b_T^2)\;,$$

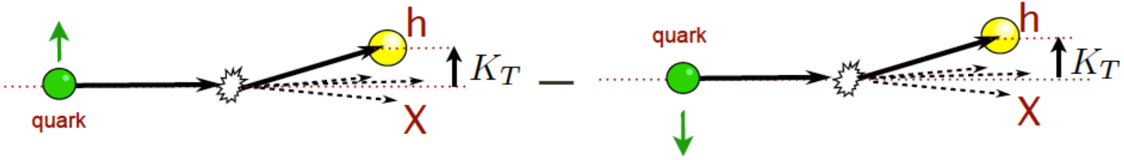
$$F_{UT}^{\sin(3\phi_h-\phi_S)} = x_B \sum_a e_a^2 \int \frac{d|b_T|}{(2\pi)}|b_T|^4 J_3(|b_T||P_{h\perp}|)\frac{M^2 M_h z^3}{4}\tilde{h}_{1T}^{\perp(2)}(x, z^2 b_T^2)\; \tilde{H}_1^{\perp(1)}(z, b_T^2)\;.$$



- With different Bessel weights BGMP provides a model independent way to extract k_T-dependences for all TMDs
- requires wide range in hadron P_T

Transversity: single-hadron vs di-hadron

No simple way to extract transversity

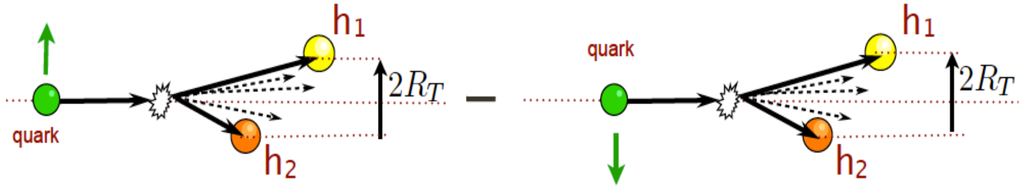


$$F_{UT}^{\sin(\phi_h+\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h} h_1 H_1^{\perp}\right]$$

$$\mathcal{C}[w\,f\,D] = x\sum_a e_a^2 \int d^2\boldsymbol{p}_T\, d^2\boldsymbol{k}_T\, \delta^{(2)}\left(\boldsymbol{p}_T - \boldsymbol{k}_T - \boldsymbol{P}_{h\perp}/z\right) w(\boldsymbol{p}_T, \boldsymbol{k}_T)\, f^a(x, p_T^2)\, D^a(z, k_T^2)$$

Compare single hadron and dihadron SSAs

M.Radici

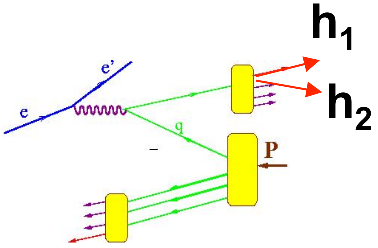


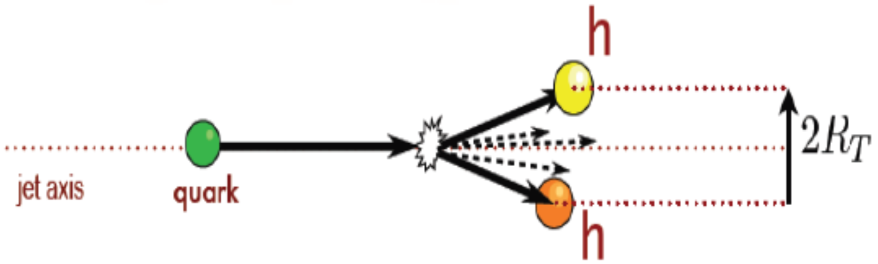
$$F_{UT}^{\sin(\phi_R+\phi_S)} = B(y)\,\sin(\phi_R+\phi_S)\,\frac{|\vec{R}_T|}{M_h}\,h_1(x)\,H_1^{\sphericalangle}(z,\zeta,M_h^2)$$

In dihadron production we deal with the product of functions instead of convolution

Dihadron Fragmentation

z_1, z_2 - fractions of energy carried by a hadrons

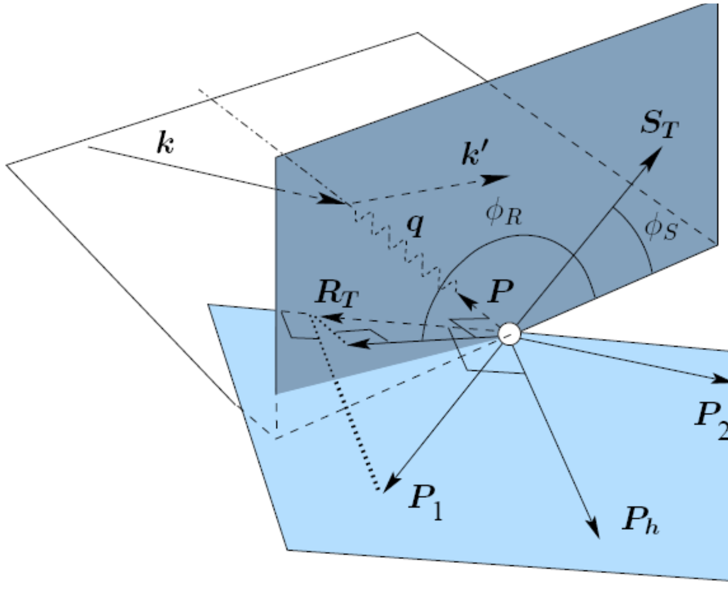


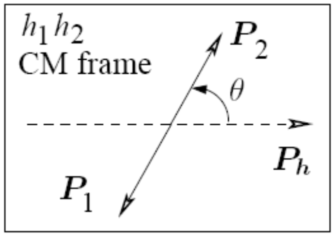


DiFF

$$D_1^{q \to h_1, h_2}(z_1, z_2, R_T^2)$$

- Factorization proven
- Evolution known
- Extracted at BELLE for ππ pairs, planned for πK pairs



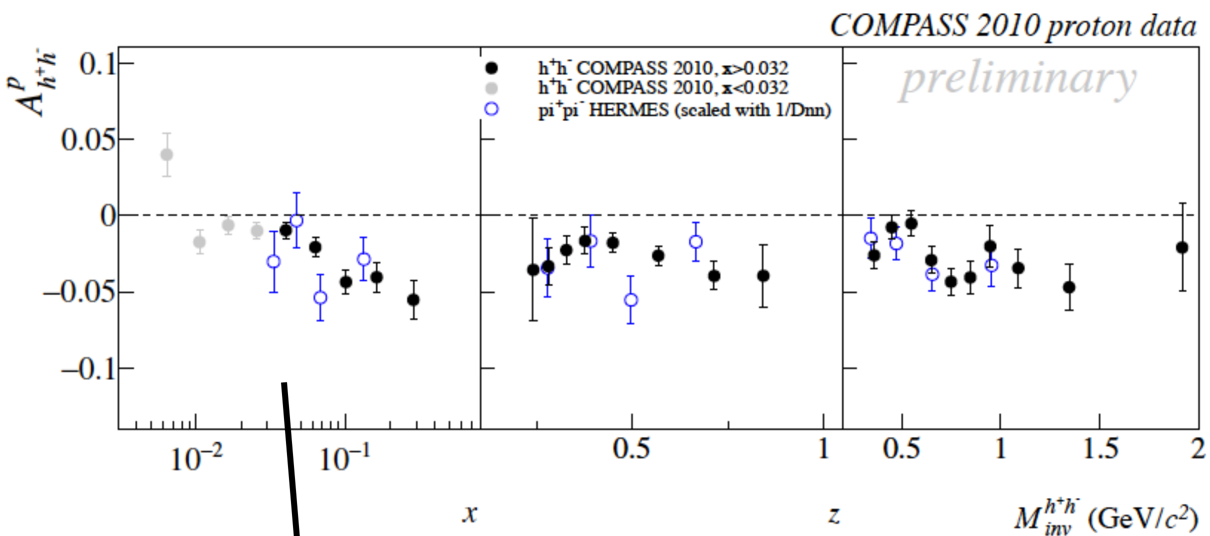


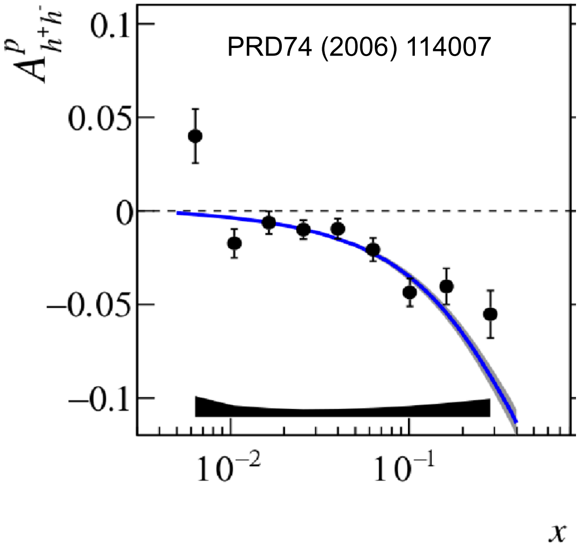
$$R_T =$$

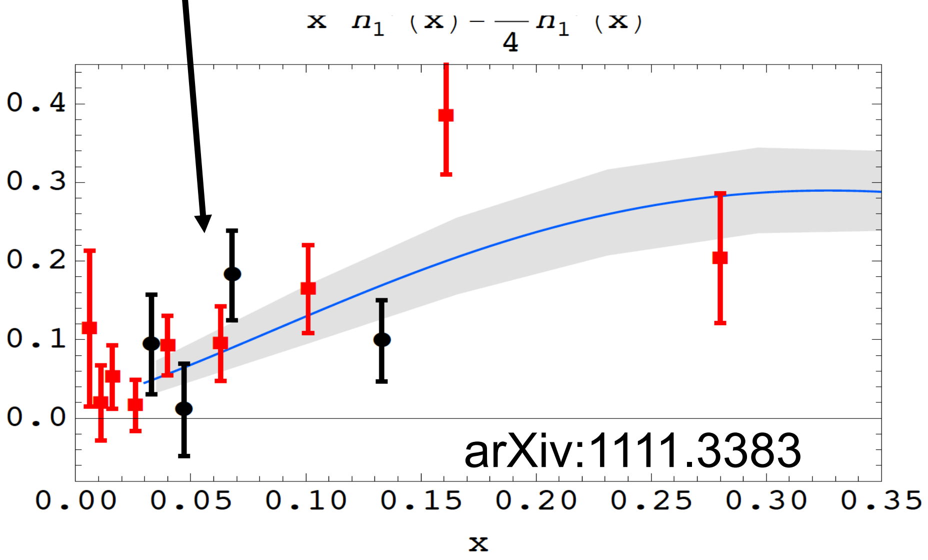
$$R \equiv (P_1 - P_2)/2$$

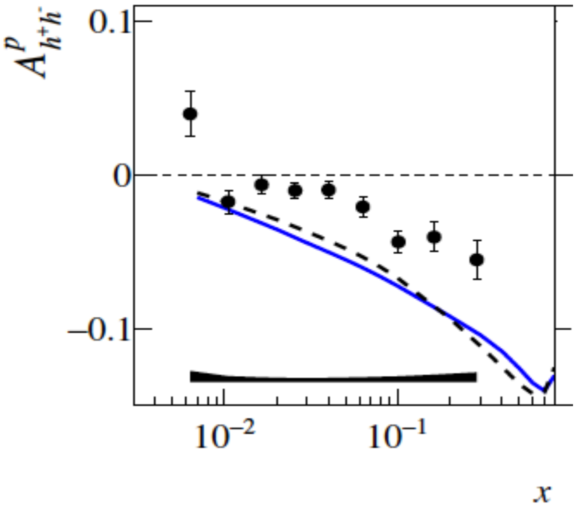
Dihadron productions offers exciting possibility to access transversity distribution

Dihadron production with transversely polarized target


COMPASS 2010 proton data

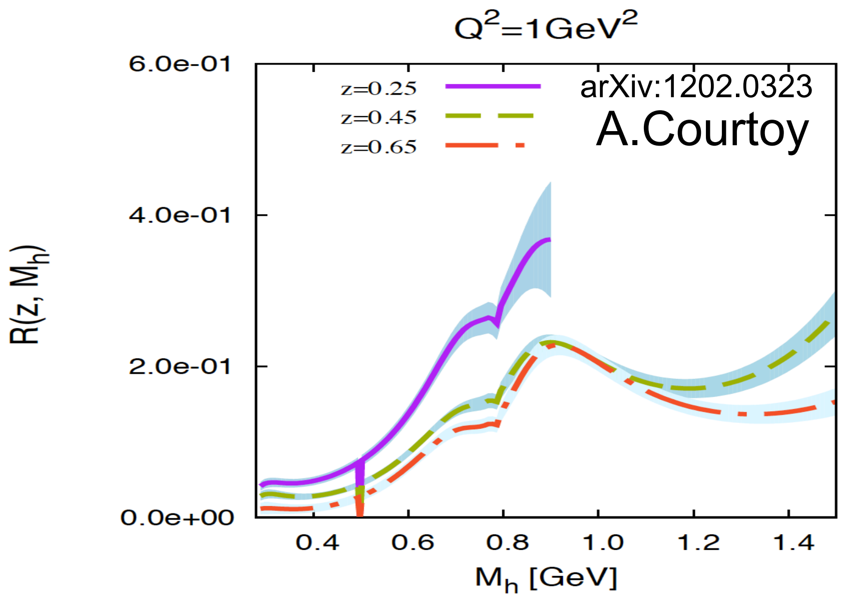

PRD74 (2006) 114007


arXiv:1111.3383



Significant asymmetries observed at HERMES and COMPASS
Large acceptance of CLAS12 makes dihadron production a perfect tool to extract transversity

Dihadron Fragmentation

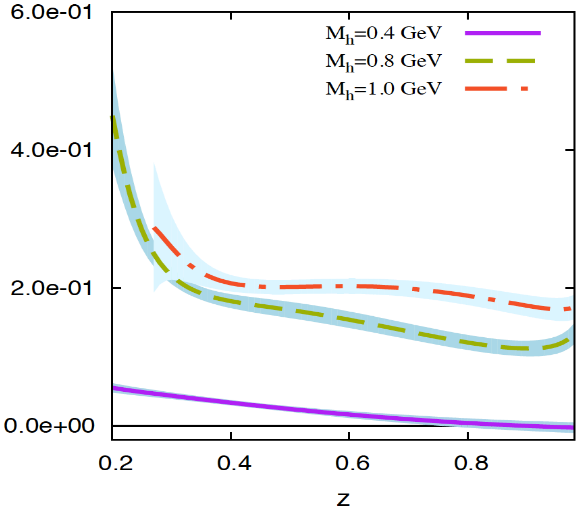


Q^2=1GeV^2

arXiv:1202.0323

A.Courtoy

- Significant DiFF published by BELLE

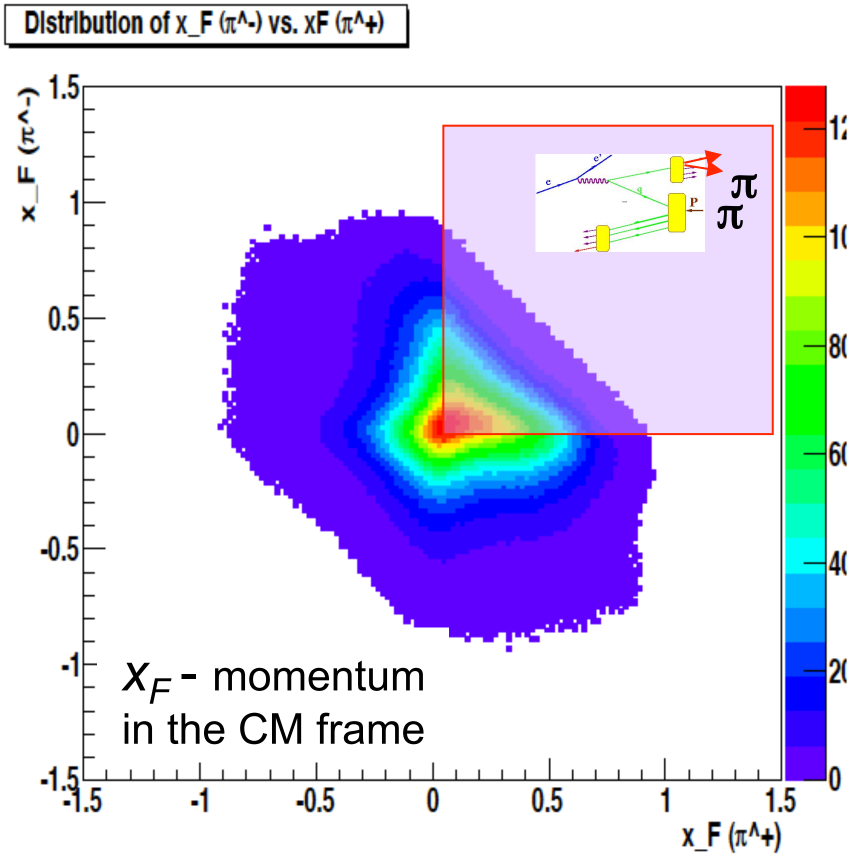


$$A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta}(x,y,z,M_h,Q) = -\frac{B(y)}{A(y)}\,\frac{|\mathbf{R}|}{M_h}\,\frac{x}{x}\,\frac{\sum_q e_q^2\, h_1^q(x)\, H_{1,sp}^{\sphericalangle,q}(z,M_h)}{\sum_q e_q^2\, f_1^q(x)\, D_{1,ss+pp}^q(z,M_h)}$$

$$\frac{n^u_{H_1^{\sphericalangle}}}{n^u_{D_1}}(\sim 2\ \mathrm{GeV}^2)\Big/\frac{n^u_{H_1^{\sphericalangle}}}{n^u_{D_1}}(100\ \mathrm{GeV}^2) = 92\% \pm 8\%$$

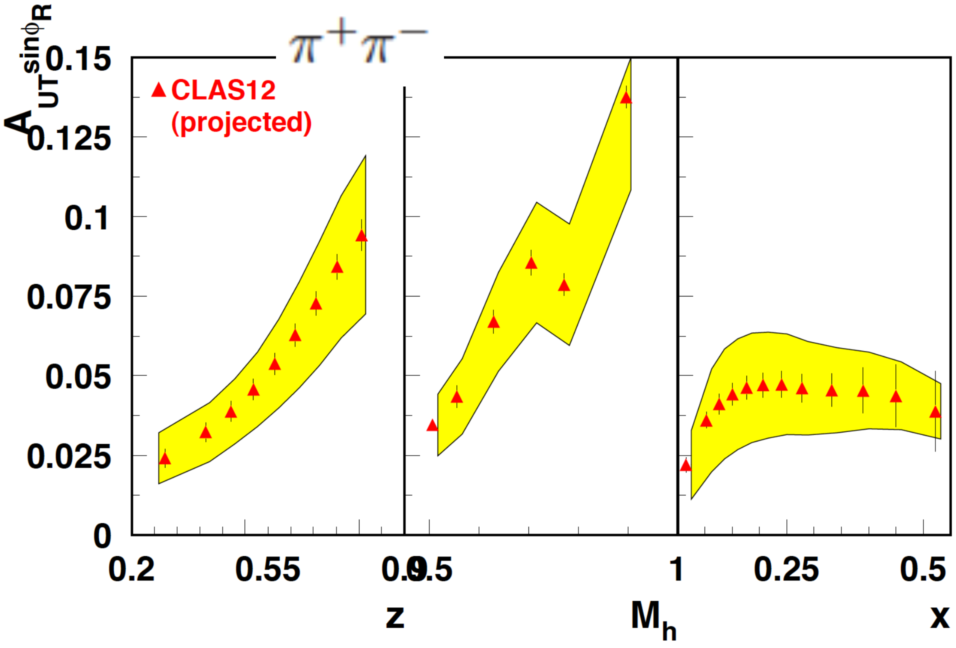
- Evolution effects small for DiFF/D_1
- DiFF represent the easiest way to measure the polarization of a fragmenting quark
- DiFF contain information on interferences between different channels (e.g., rho and continuum), which cannot be encoded in MC generators based on the Lund model

Dihadron production with CLAS12



x_F - momentum in the CM frame

100 days of transversely polarized HD (proton)



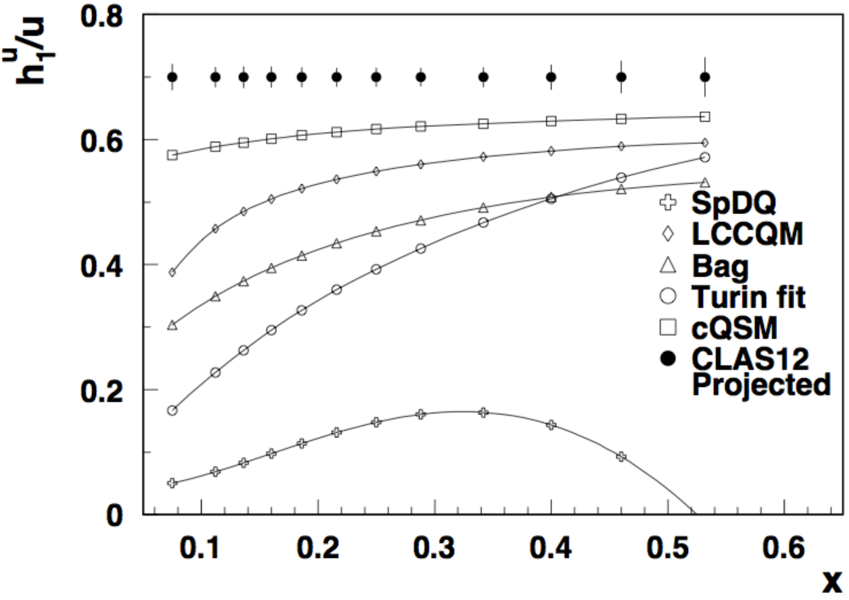
CLAS12 will provide precision measurements of single target asymmetries in dihadron pair production in SIDIS

Dihadron production with CLAS12

$$\frac{x\,h_1^u(x)}{x\,f_1^u(x)} = -\frac{A(y)}{B(y)}\left(\frac{|\mathbf{R}|}{M_h}\right)^{-1}\frac{D_1^u(z,M_h)}{H_1^{\sphericalangle,u}(z,M_h)}A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta}(x,y,z,M_h,Q)$$

SU(6)

$$\frac{17}{18}\,\frac{x\,h_1^u(x)}{x\,f_1^u(x)} \models -\frac{A(y)}{B(y)}\left(\frac{|\mathbf{R}|}{M_h}\right)^{-1}\frac{D_1^u(z,M_h)}{H_1^{\sphericalangle,u}(z,M_h)}A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta}$$



$$D_1^u(z,M_h) \approx D_1^d(z,M_h)$$

100 days of transversely polarized HD will allow precision measurement of the transversity distribution.

Summary

- **Current JLab data are consistent with a partonic picture:**
  - **The data consistent with factorization (no x/z-dependence observed in single and double spin asymmetry measurements).**
  - **Measured spin and azimuthal asymmetries asymmetries ($<\sin\phi>$, $<\sin(\phi+/-\phi_S)>$, $<\sin 2\phi>$, …), are in agreement with theory predictions and measurements at higher energies**

- **Measurements of azimuthal dependences of double and single spin asymmetries in SIDIS indicate that there are significant correlations between spin and transverse distribution of quarks.**

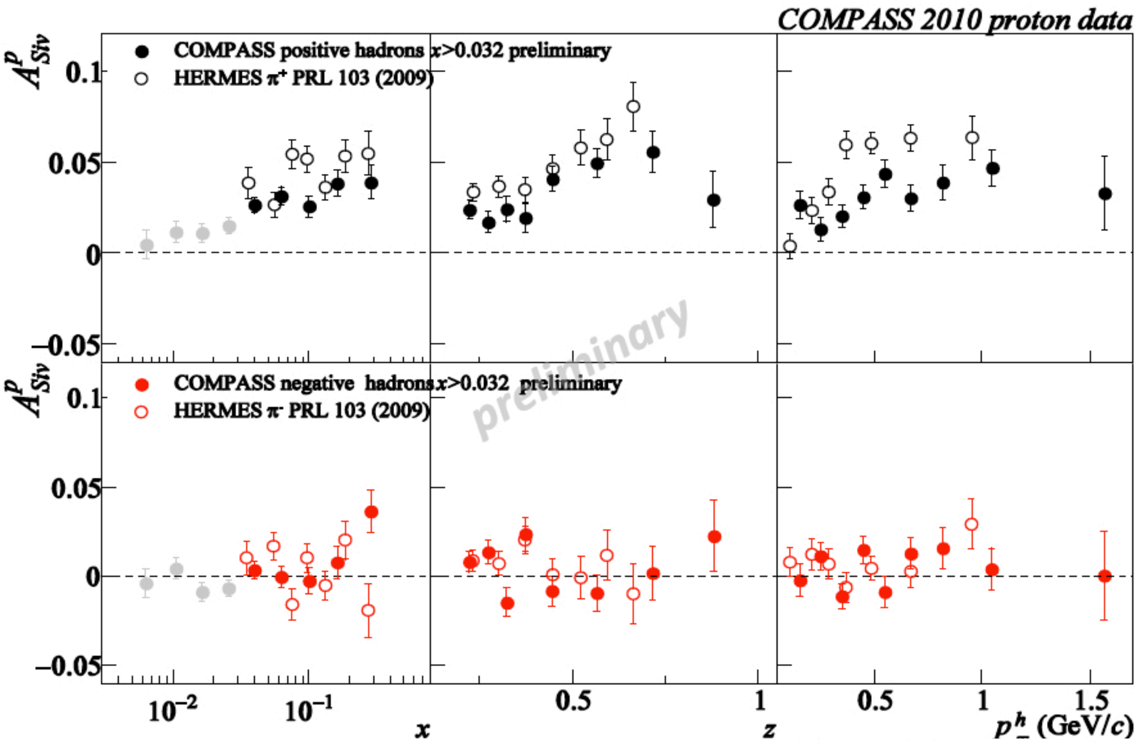
- **Sizable higher twist asymmetries measured both in SIDIS and exclusive production indicate the quark-gluon correlations may be significant at moderate Q^2.**

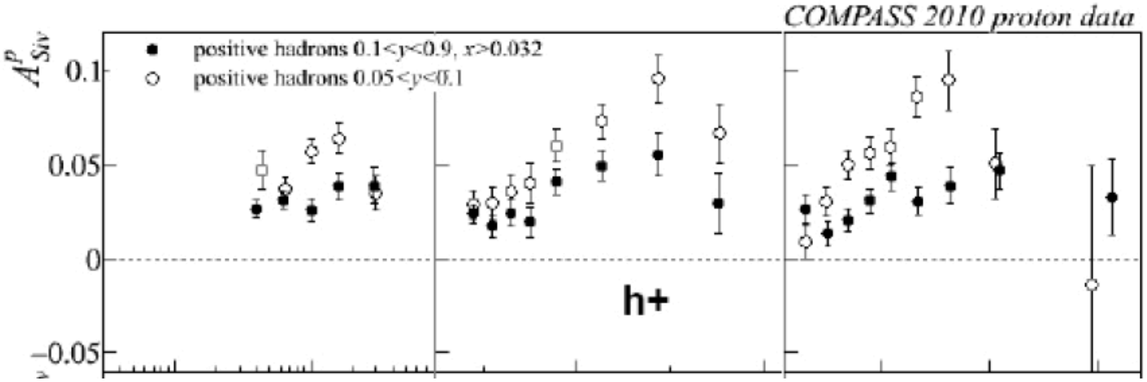
- **k_T-dependent flavor decomposition is required to extract the PDFs in multidimensional space in a model independent way**

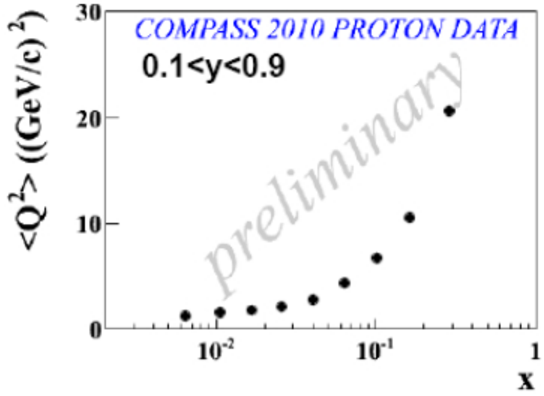
Measurements of TMDs at Jlab & JLab12 in the valence region will provide important input into the global analysis of Transverse Momentum Distributions (involving HERMES,COMPASS,RHIC,BELLE,BABAR)

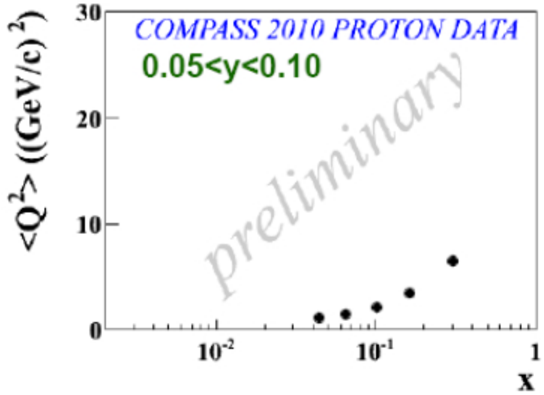
Support slides….

TMDs from different experiments



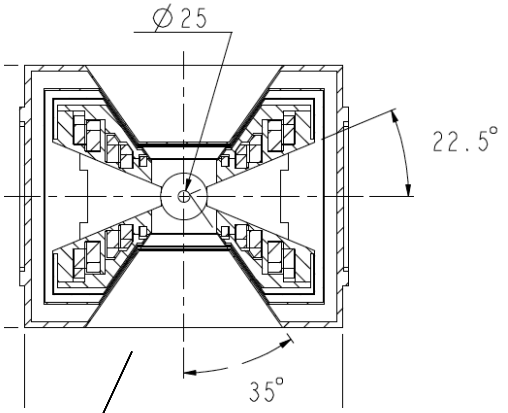




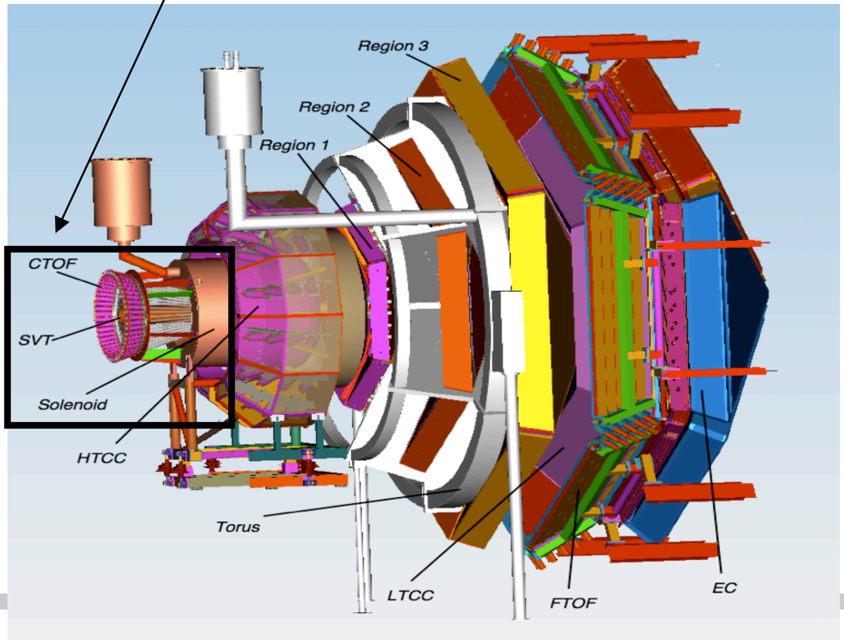


Data suggests Q^2 evolution of Sivers function may be significant

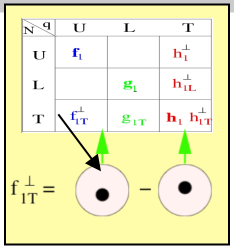
Studies of the Sivers asymmetry with CLAS12

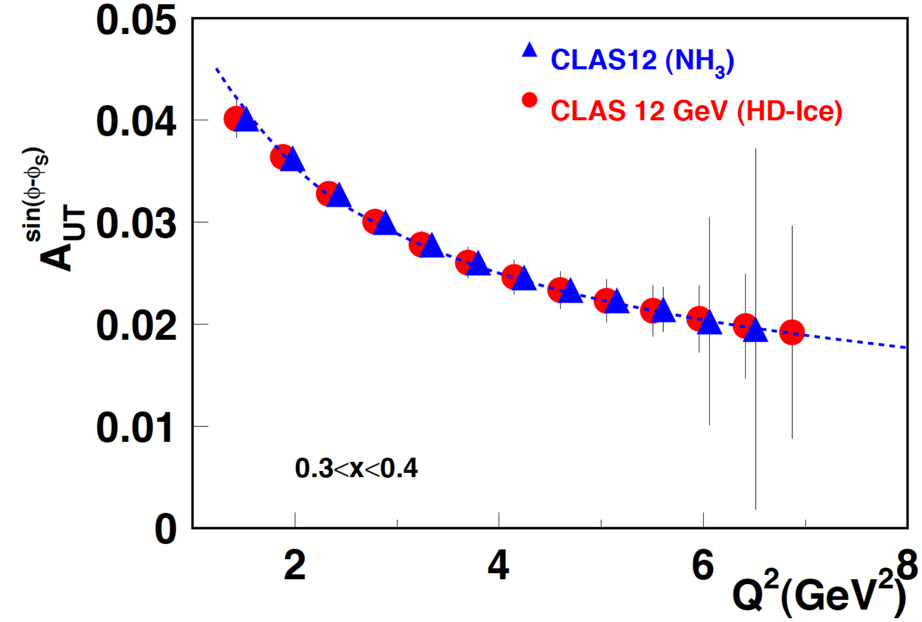


Replace the central detector with the transverse target



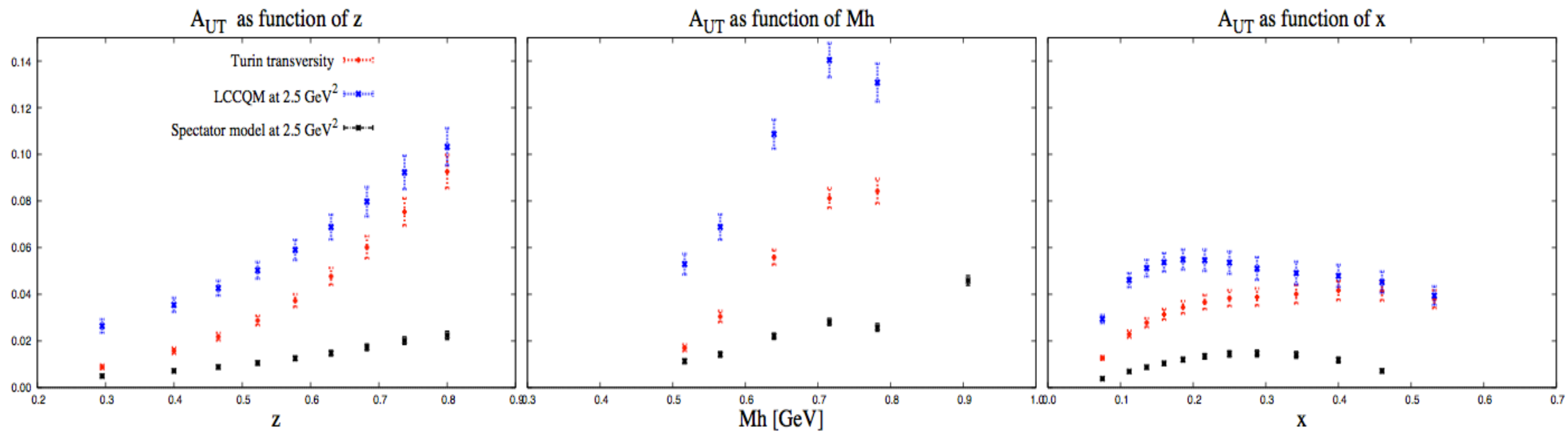
$$A_{UT}^{\sin(\phi-\phi_S)} = \frac{\sum_q e_q^2 f_{1T}^{\perp q} D_1^q}{\sum_q e_q^2 f_1^q D_1^q}$$





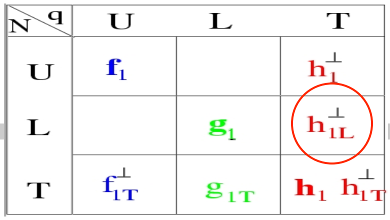
Higher luminosity with 4.2T magnet will provide comparable to full acceptance coverage up to 6 GeV in Q^2.

Model predictions: transverse target



$$A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta}(x,y,z,M_h,Q) = -\frac{B(y)}{A(y)}\,\frac{|\mathbf{R}|}{M_h}\,\frac{x}{x}\,\frac{\sum_q e_q^2\, h_1^q(x)\, H_{1,sp}^{\sphericalangle,q}(z,M_h)}{\sum_q e_q^2\, f_1^q(x)\, D_{1,ss+pp}^q(z,M_h)}$$

- Models agree on a large target SSA for ππ pair production
- Deuteron target measurements provide complementary information on flavor dependence



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 $h_{1T}^{\perp}$

Longitudinal Target SSA measurements at CLAS

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

$W^2>4$ GeV^2

$Q^2>1.1$ GeV^2

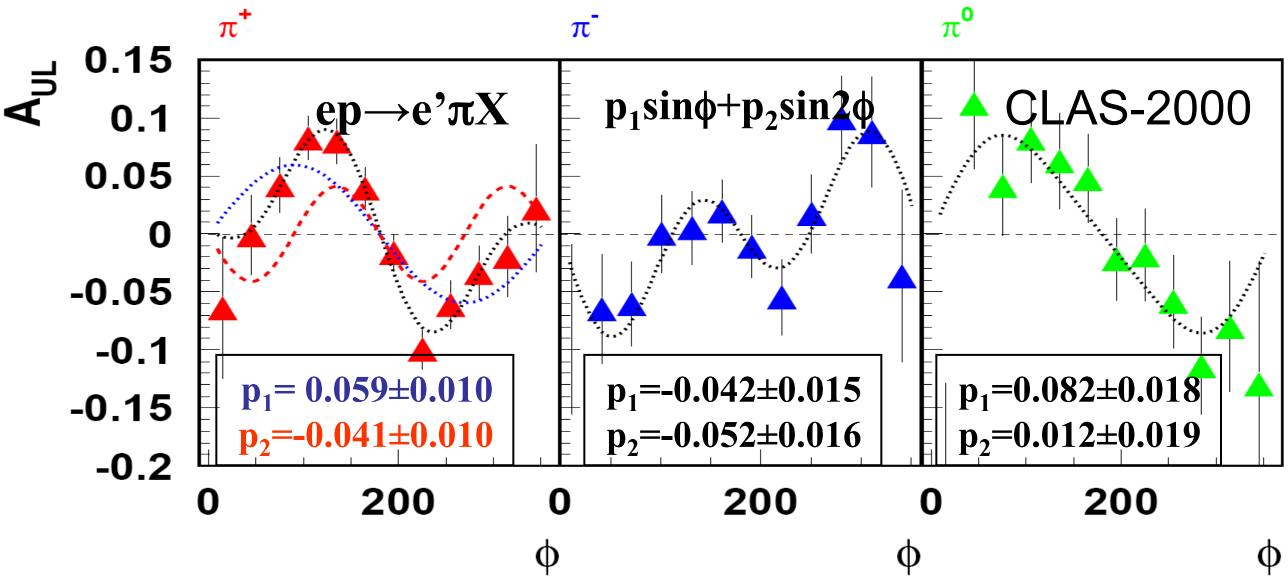
$y<0.85$

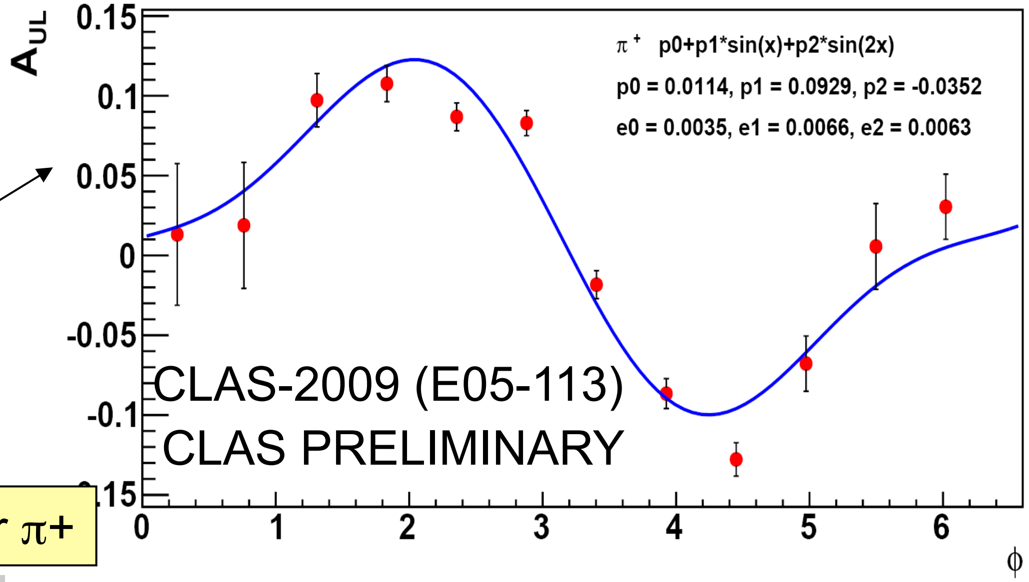
$M_X>1.4$ GeV

$P_T<1$ GeV

$0.12<x<0.48$

$0.4<z<0.7$





~10% of E05-113 data

Data consistent with negative sin2φ for π+

TMD Correlation Functions in other experiments

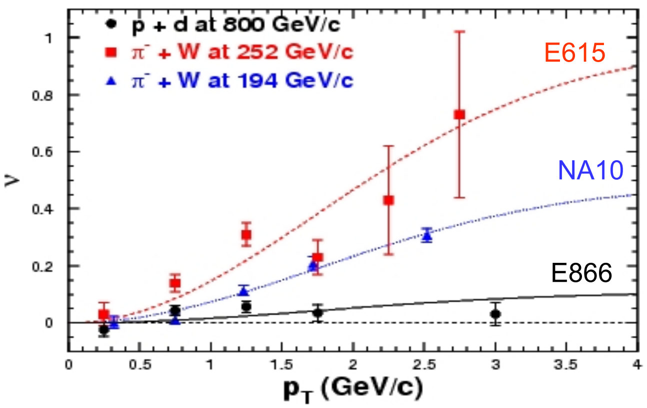
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

BOER-MULDERS

Spin Orbit effect

$$\nu \approx h_{1q}^\perp \times h_{1\bar{q}}^\perp$$

hp → μμX



Fragmentation Functions (FF)

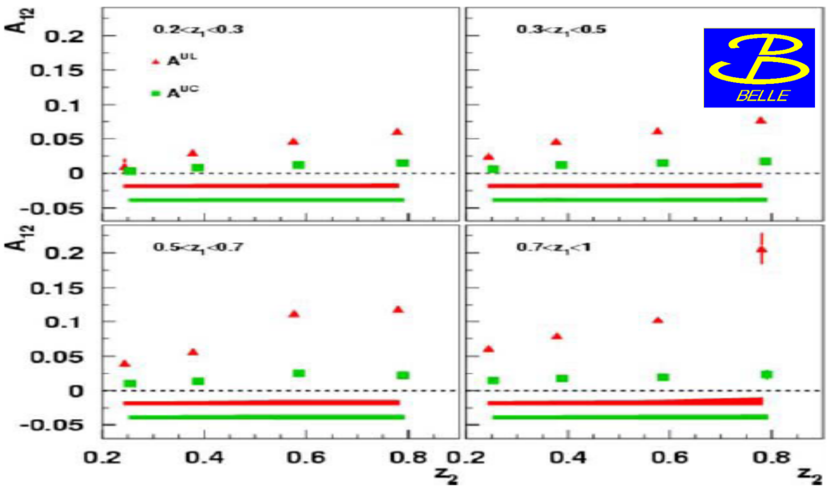
q/h	U
U	D_1
T	$H_1^\perp$

COLLINS

Quark spin probe

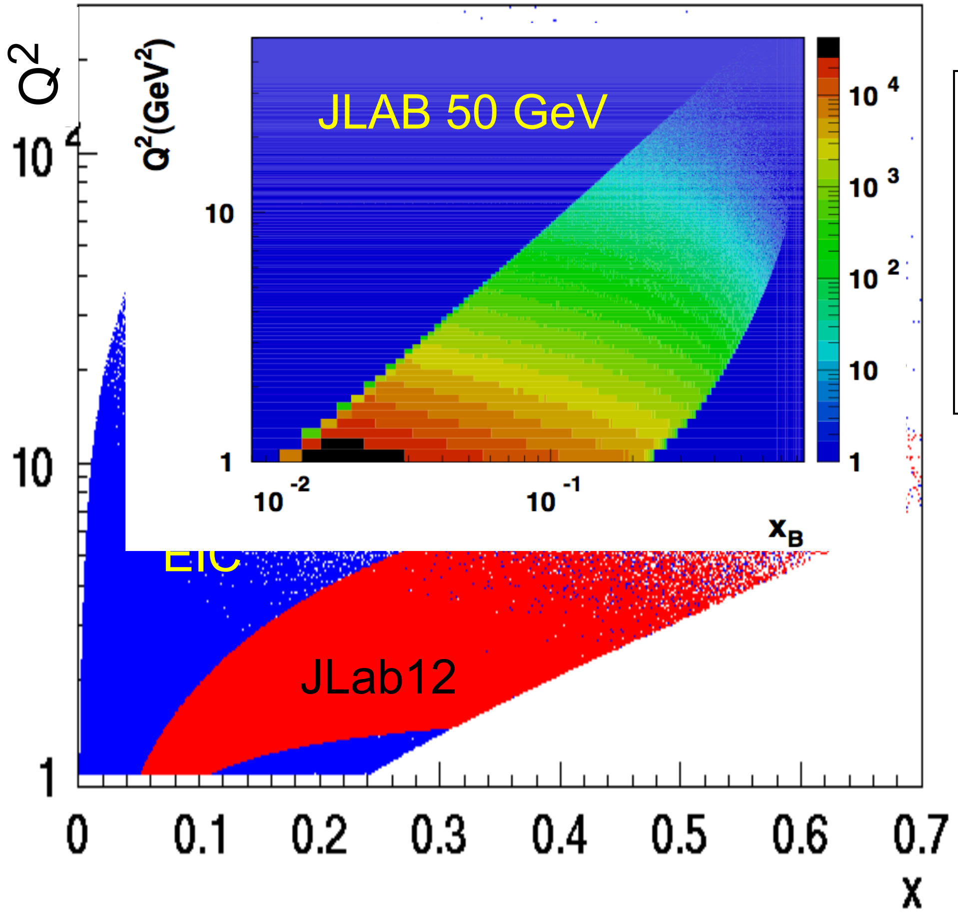
$$A_{12} \approx H_{1q}^\perp \times H_{1\bar{q}}^\perp$$

ee → ππX



In di-hadron case $H_1^{\sphericalangle}$ Interference Fragmentation Function (IFF)

Hard Scattering Processes: Kinematics Coverage



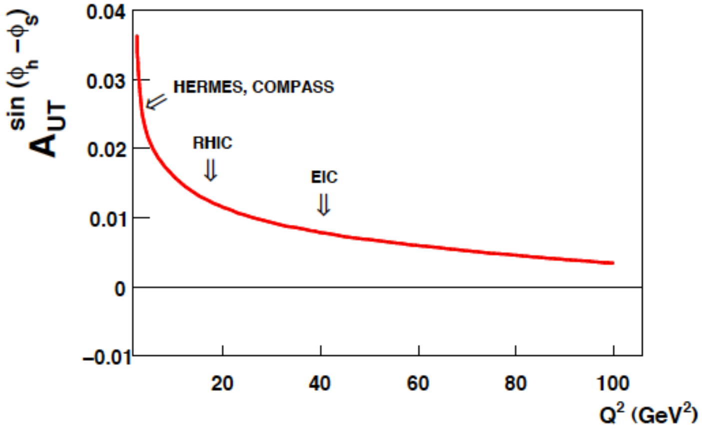
JLab@12GeV (25/50/75)

→$0.1<x_B<0.7$: valence quarks

EIC √s = 140, 50, 15 GeV

→$10^{-4}<x_B<0.3$: gluons and quarks, higher P_T and Q^2.

Aybat,Prokudin&Rogers arXiv:1112.4423



- Study of high **x** domain requires high luminosity, low **x** higher energies
- Wide range in Q^2 is crucial to study the evolution
- Overlap of EIC and JLab12 in the valence region will be crucial for the TMD program

Model predictions: transverse target

$$A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta}(x,y,z,M_h,Q) = \frac{1}{|\mathbf{S_T}|}\frac{\frac{8}{\pi}\int d\phi_R\, d\cos\theta\ \sin(\phi_R+\phi_S)\left(d\sigma^{\uparrow}-d\sigma^{\downarrow}\right)}{\int d\phi_R\, d\cos\theta\,(d\sigma^{\uparrow}+d\sigma^{\downarrow})}$$

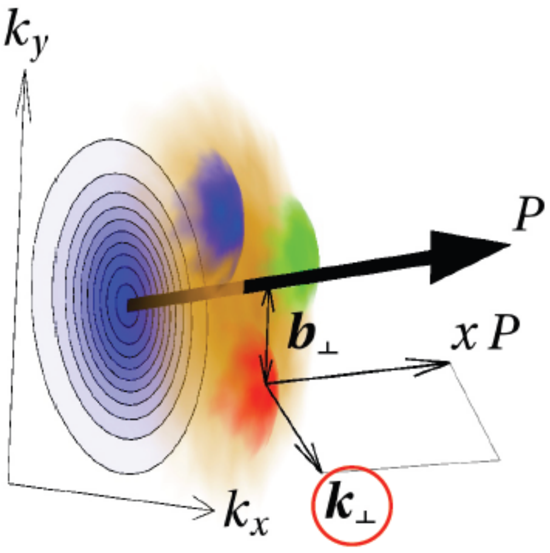
$$= \frac{\frac{4}{\pi}\varepsilon\int d\cos\theta\, F_{UT}^{\sin(\phi_R+\phi_S)}}{\int d\cos\theta\ (F_{UU,T}+\epsilon F_{UU,L})}\ . \qquad (1)$$

Leading twist

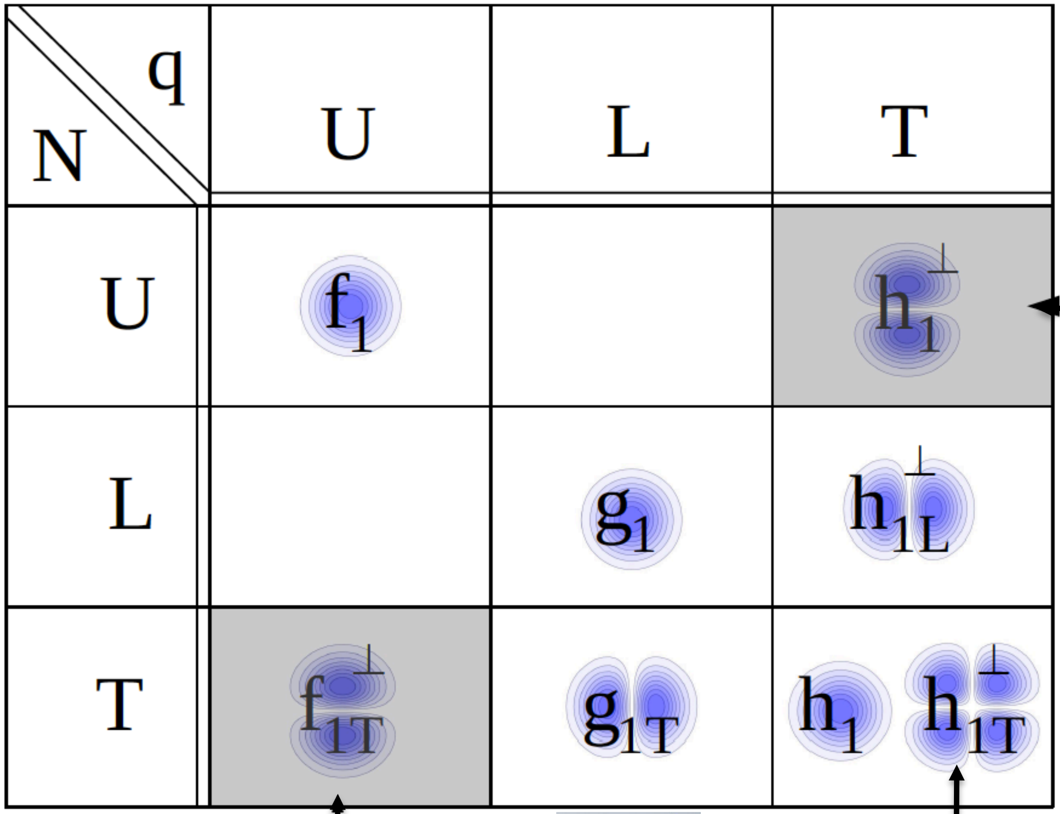
$$A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta}(x,y,z,M_h,Q) = -\frac{B(y)}{A(y)}\frac{|\mathbf{R}|}{M_h}\frac{x}{x}\frac{\sum_q e_q^2\, h_1^q(x)\, H_{1,sp}^{\sphericalangle,q}(z,M_h)}{\sum_q e_q^2\, f_1^q(x)\, D_{1,ss+pp}^q(z,M_h)}$$

- Models agree on a large target SSA for ππ pair production
- Deuteron target measurements provide complementary information on flavor dependence

Transverse Momentum Dependent (TMD) Distributions



GTMD/Wigner distribution



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

pretzelosity

Transverse Momentum Distributions (TMDs) of partons describe the distribution of quarks and gluons in a nucleon with respect to x and the intrinsic transverse momentum k_T carried by the quarks

SIDIS (γ*p→πX) : k_T-dependences

$$\frac{d\sigma}{dx_B\, dy\, d\psi\, dz\, d\phi_h\, dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\left\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}\right\},$$

$f_1 \otimes D_1$

HT

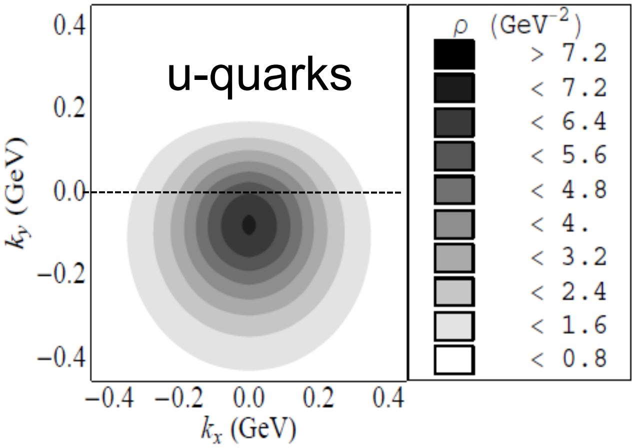
HT

$h_1^\perp \otimes H_1^\perp$

HT

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

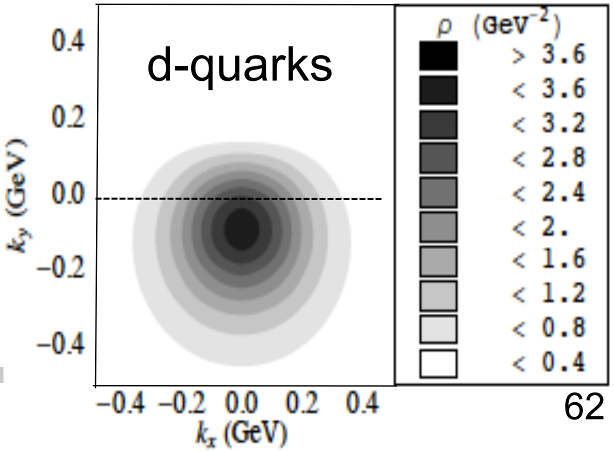
Pasquini&Yuan(2010)



BM TMD (1998) describes correlation between the transverse momentum and transverse spin of quarks, requires FSI or ISI

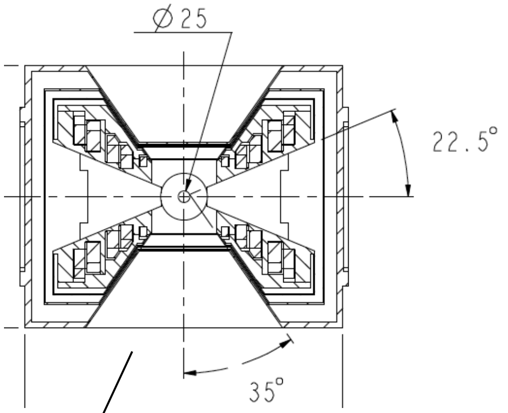
$$f_{q/p}(x,k_\perp^2) = \frac{1}{2}\left[f_1^q(x,k_\perp^2) - h_1^{\perp q}(x,k_\perp^2)\frac{(\hat{P}\times k_\perp)\cdot S_q}{M}\right]$$

$$h_1^{\perp q}(SIDIS) = -h_1^{\perp q}(DY)$$

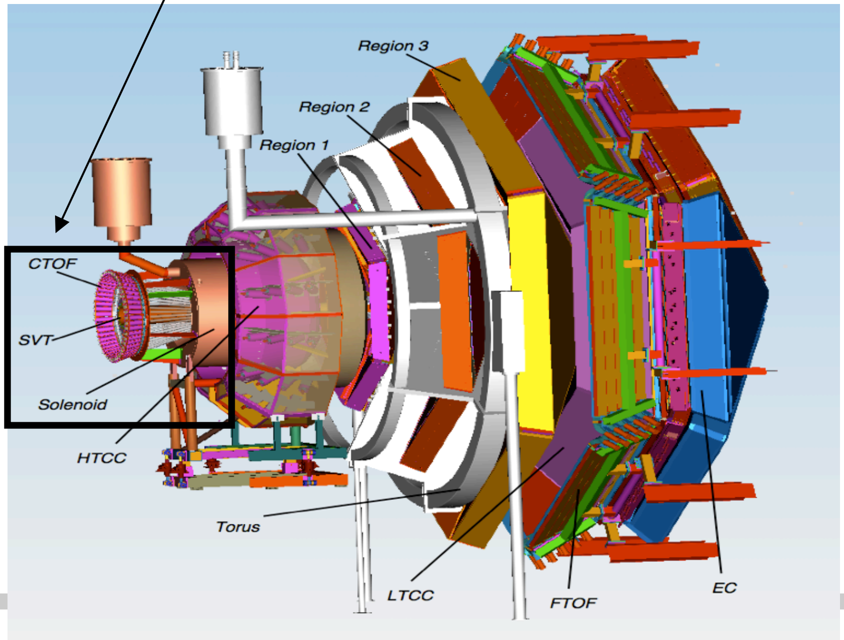


BM TMD under intensive studies worldwide, including SIDIS and DY experiments, model calculations, lattice simulations.

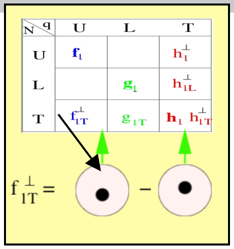
Studies of the Sivers asymmetry with CLAS12



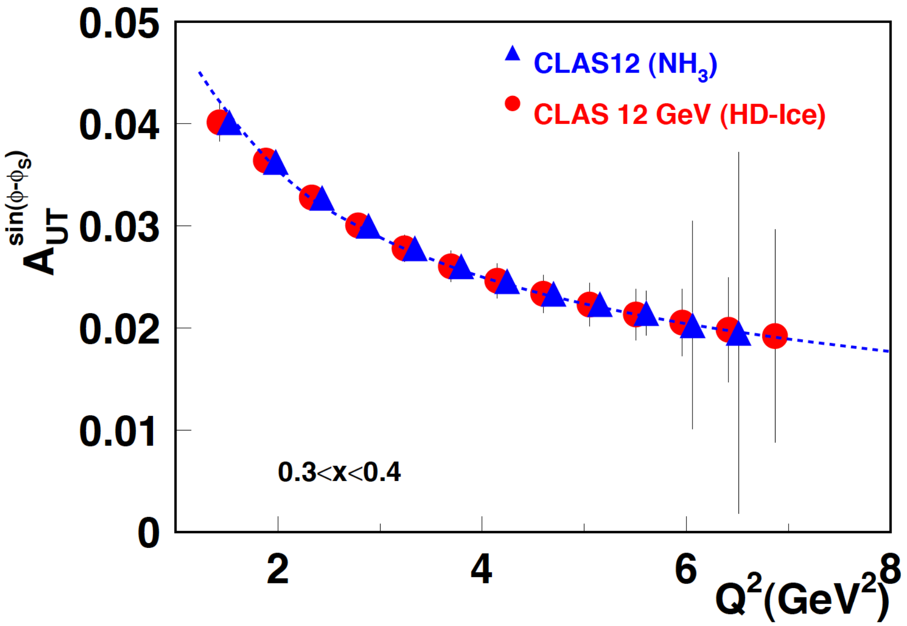
Replace the central detector with the transverse target



$$A_{UT}^{\sin(\phi-\phi_S)} = \frac{\sum_q e_q^2 f_{1T}^{\perp q} D_1^q}{\sum_q e_q^2 f_1^q D_1^q}$$

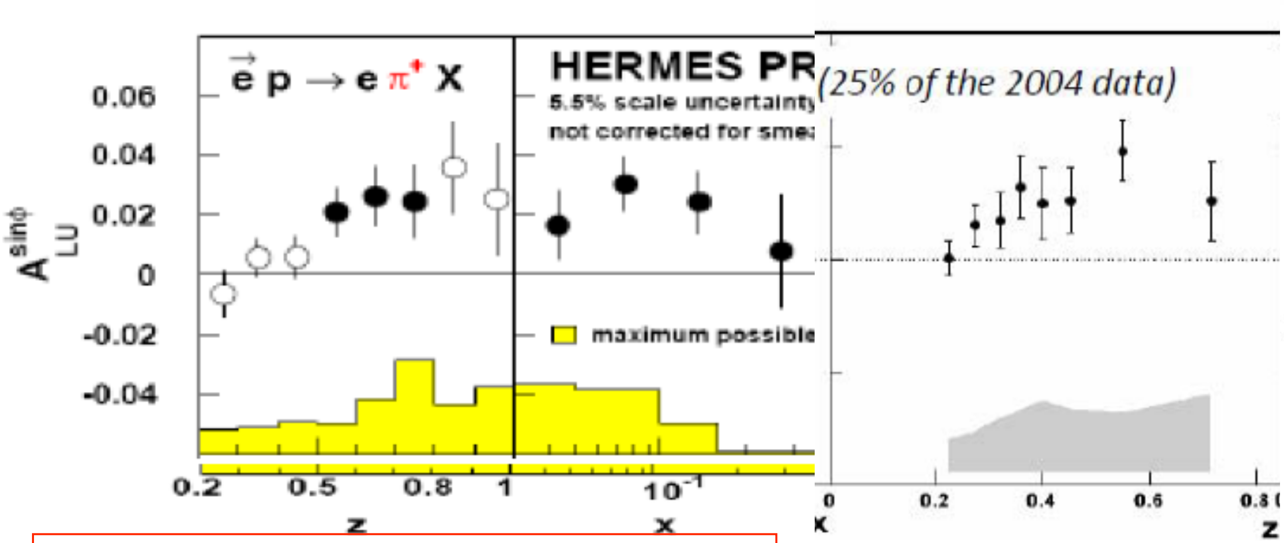


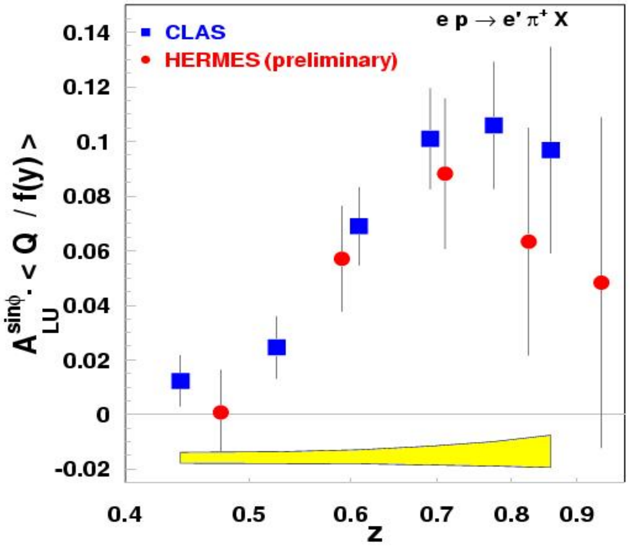
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$



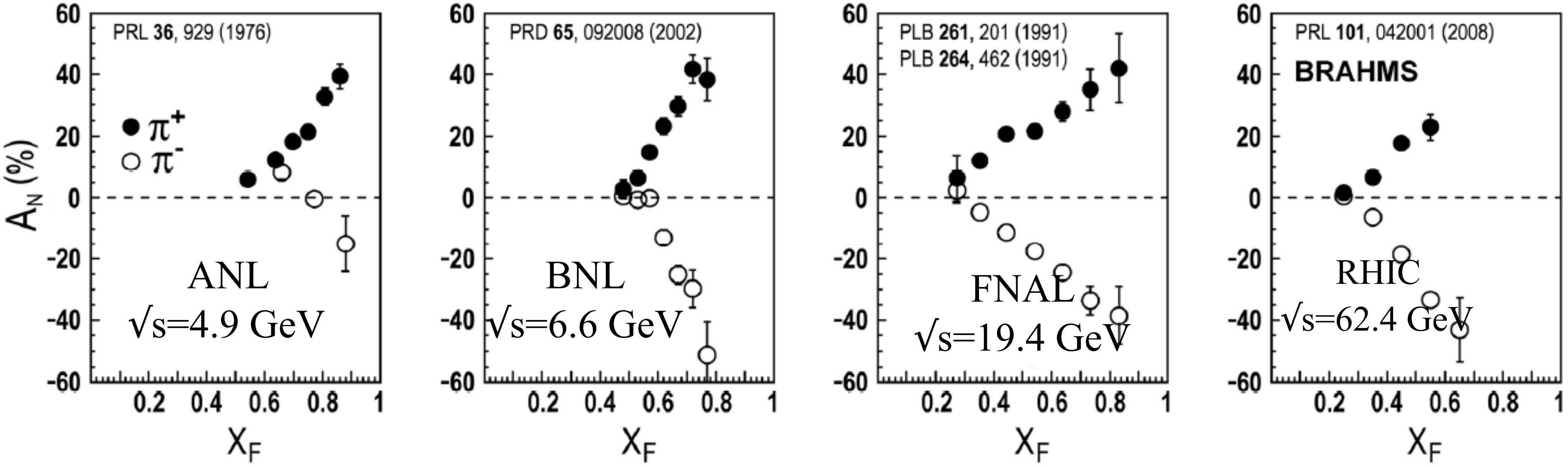
Higher luminosity with 4.2T magnet will provide comparable to full acceptance coverage up to 6 GeV in Q^2.

SSA at large x_F

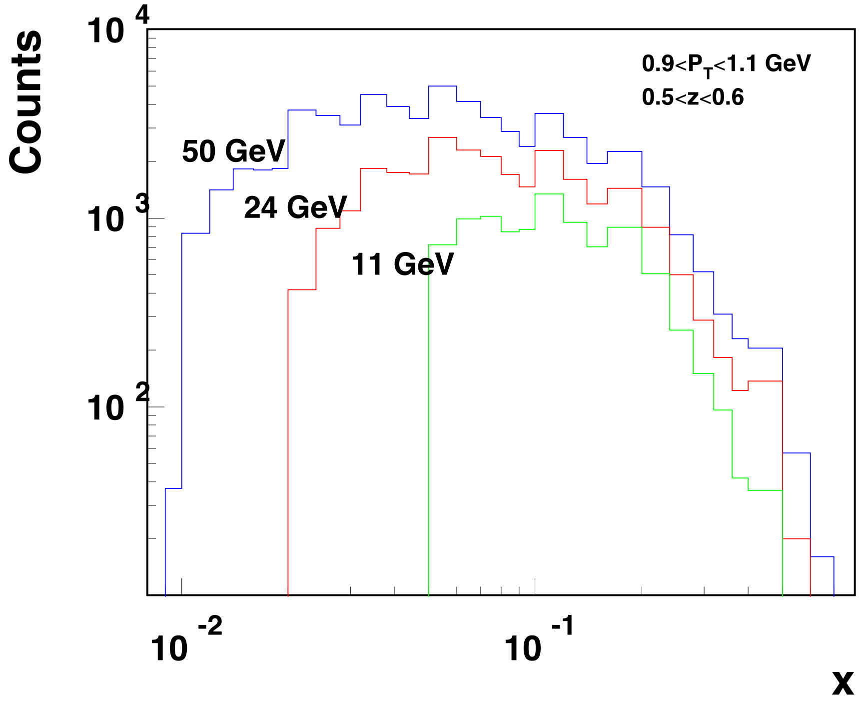




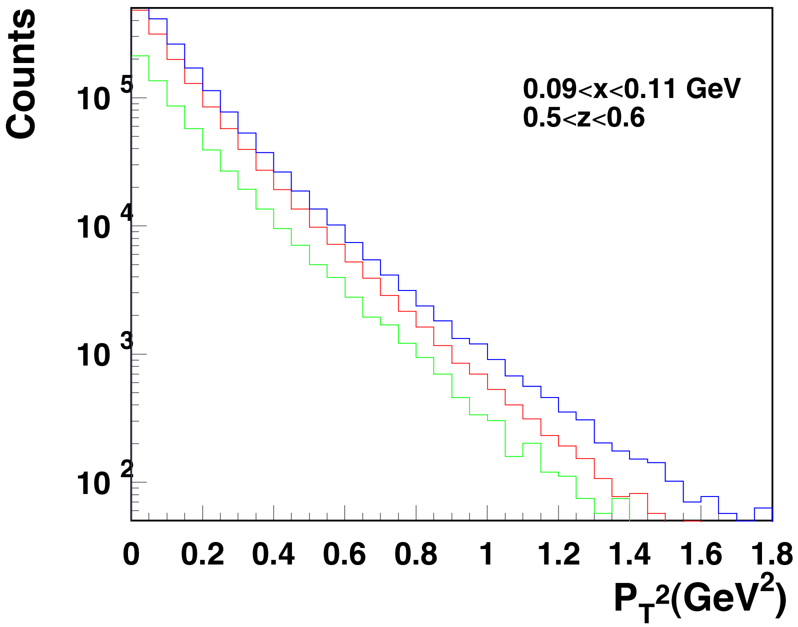
0 moves to lower x_F with energy?



$ep \rightarrow e'\pi^+X$ Kinematic coverage



Wider x range allow studies of transverse distributions of sea quarks and gluons



Wider P_T range will be important in extraction of k_T-dependences of PDFs

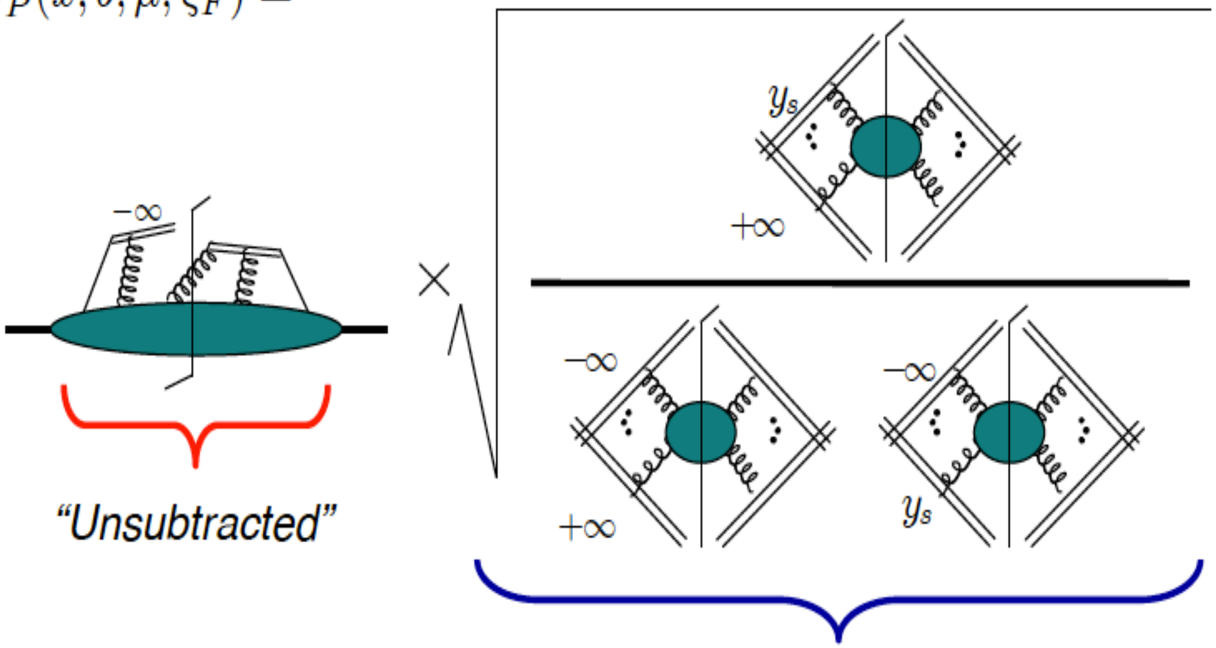
For a given lumi (30min of runtime with 10^{35}) and given bin in hadron z and P_T, higher energy provides higher counts and wider coverage in x and P_T to allow studies of correlations between longitudinal and transverse degrees of freedom

TMD PDF, Complete Definition: (Ted Rogers- Spin Session)

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 $h_{1T}^\perp$

Transverse Momentum Distributions (TMDs) of partons describe the distribution of quarks and gluons in a nucleon with respect to x and the intrinsic transverse momentum k_T (or the Fourier transform b) carried by the quarks

$$F_{f/P}(x, b; \mu; \zeta_F) =$$



"Unsubtracted"

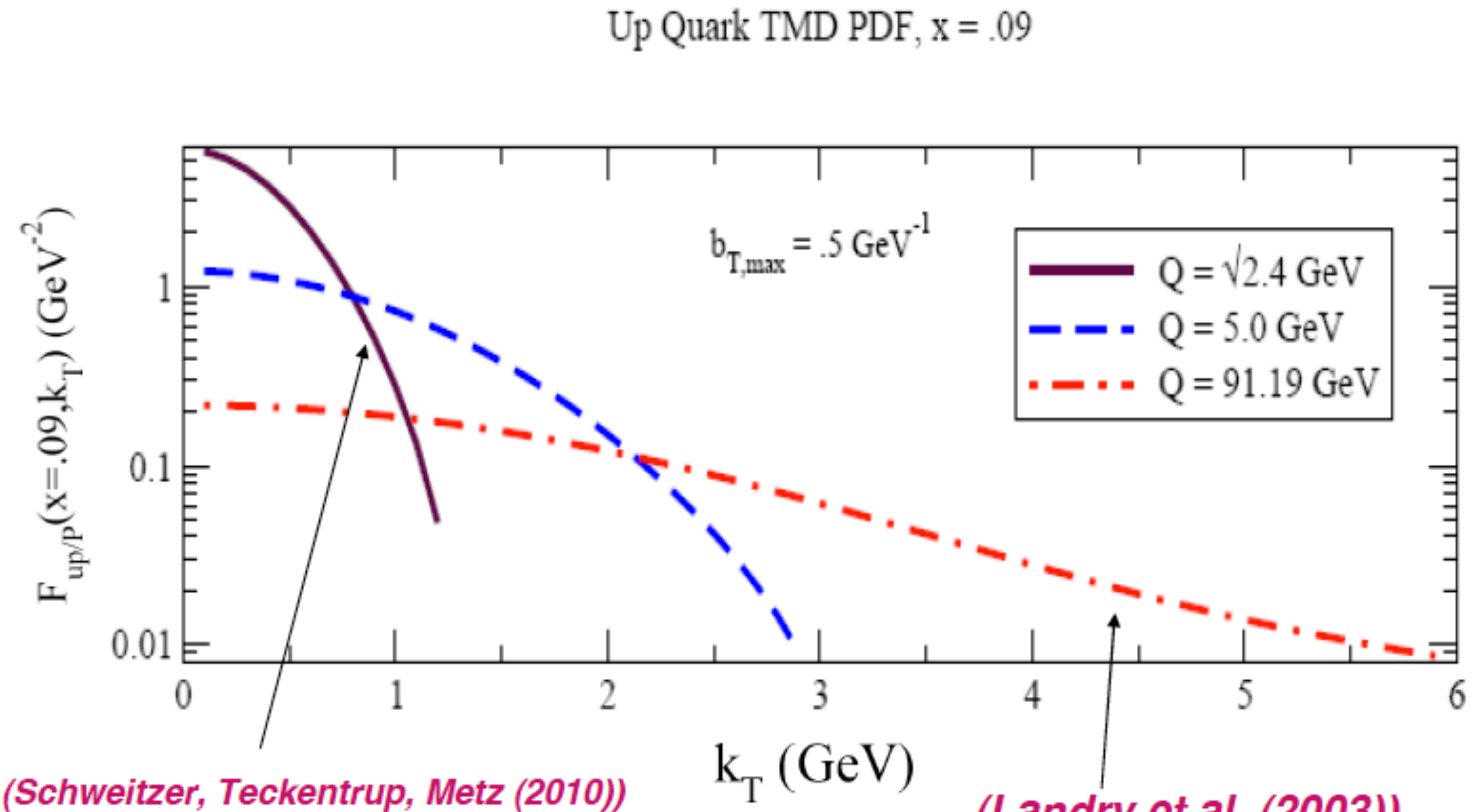
Implements Subtractions/Cancellations

***Foundations of Perturbative QCD*, J.C. Collins.**

(available May 2011)

Evolving TMD PDFs

(Ted Rogers- Spin Session)



(Schweitzer, Teckentrup, Metz (2010))

(SIDIS)

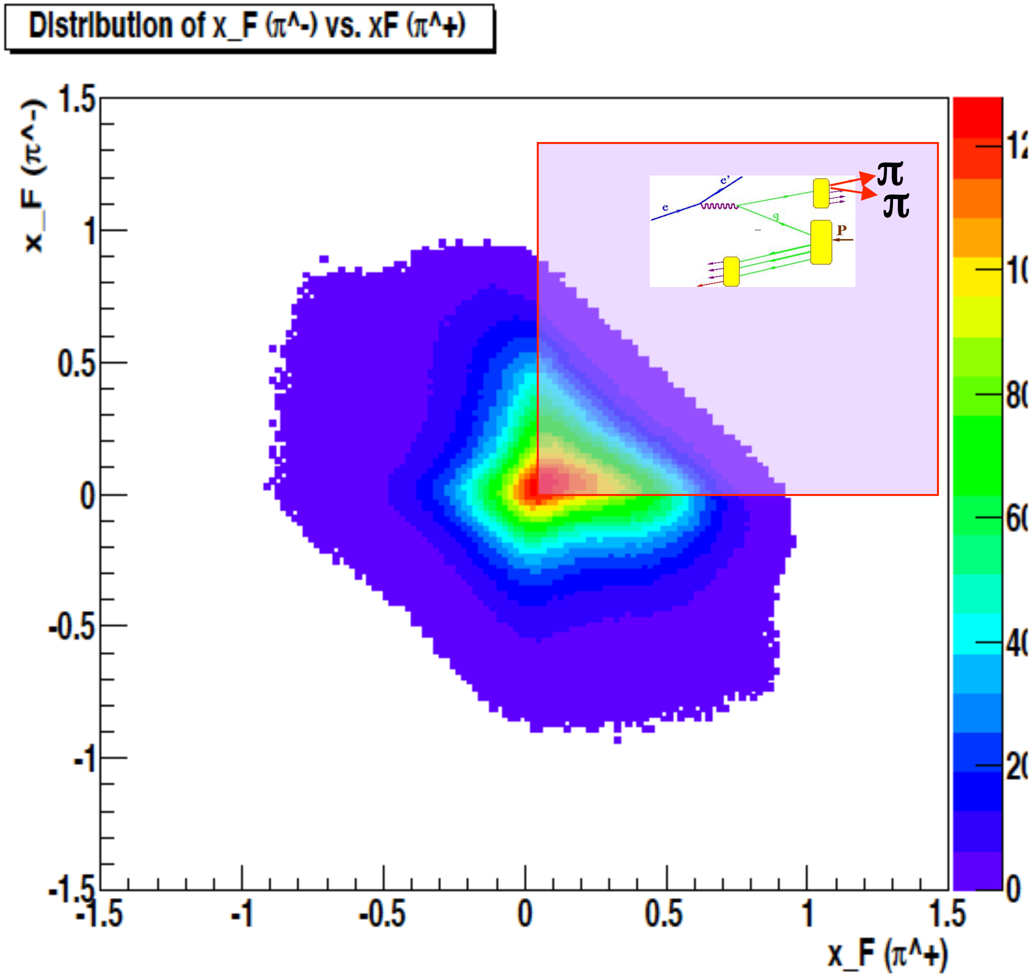
(Landry et al, (2003))

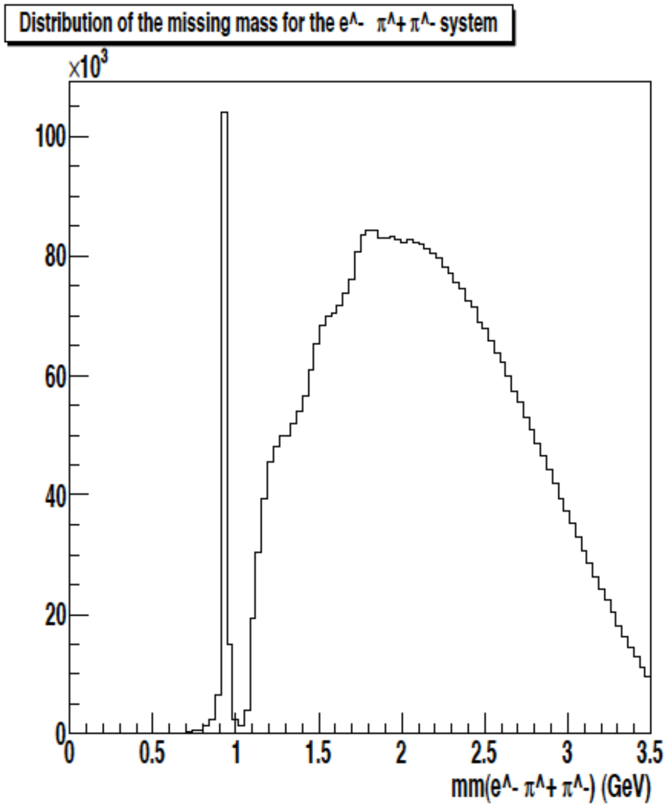
(Drell-Yan)

Dihadron production with CLAS12

Use the clasDIS (LUND based) generator + FASTMC to study $\pi\pi$ pairs

x_F - momentum in the CM frame





Dihadron sample defined by SIDIS cuts+x_F>0 (CFR) for both hadrons

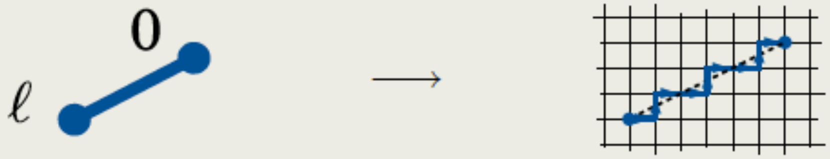
Sivers and Boer-Mulders with Lattice QCD

(Bernhard Musch- Future of DIS Session)

first exploratory lattice studies

... employ(ed) a straight gauge link

[Hägler,BM, et al. EPL ('09) and arXiv:1011.1213]



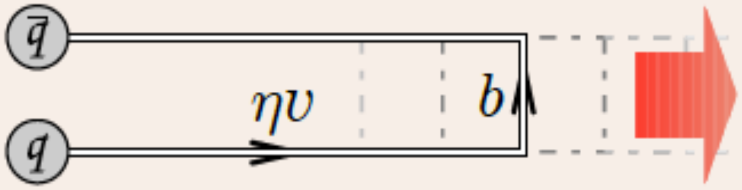
⇒ No T-odd TMDs

⇒ probably only qualitatively related to TMDs for SIDIS and Drell-Yan

Lattice studies for TMDs as in SIDIS or Drell-Yan are possible

- for ratios of Fourier-transformed TMDs
- using space-like Wilson lines as in [Aybat, Rogers arXiv:1101.5057 (2011)] and J. Collins' book (to be published)

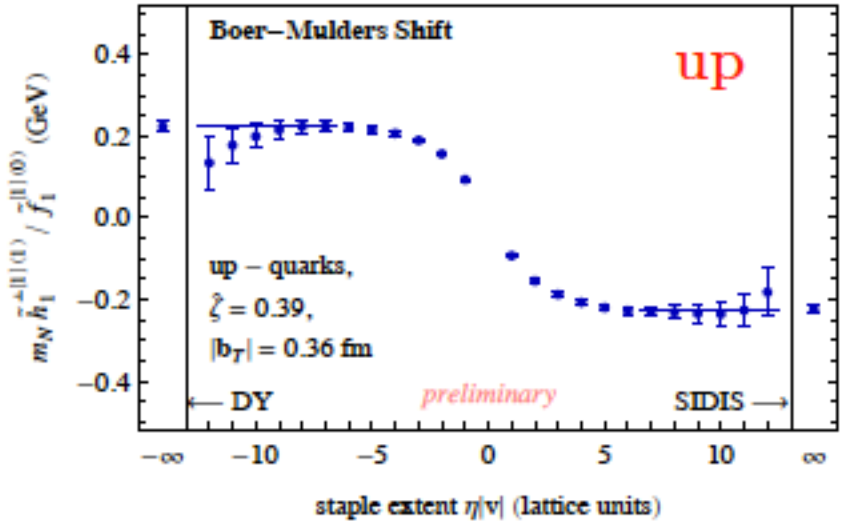
now: **staple-shaped links**



spacelike, finite length

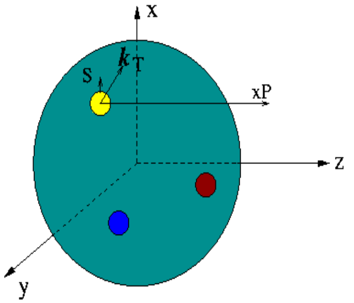
⇒ look for plateau at large η

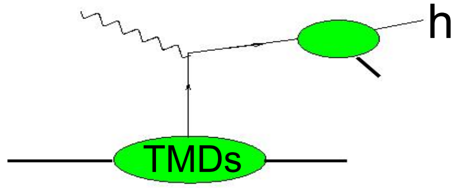
limitations: $\hat{\zeta}_{\max} = \frac{|\boldsymbol{P}_{\text{lat}}|}{m_N}$, $\sqrt{-b^2} \gtrsim 3a$



3D structure of the nucleon

Semi-Inclusive processes and transverse momentum distributions

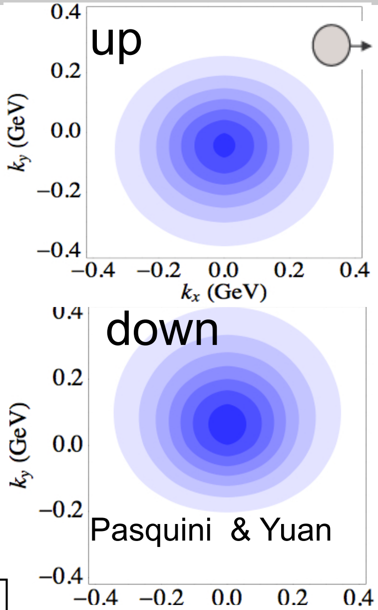




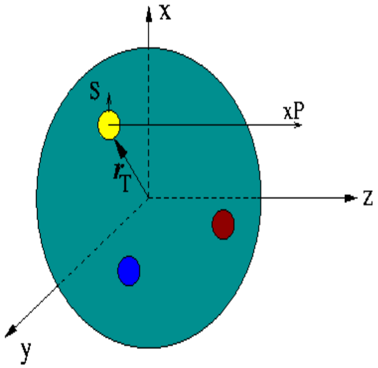
$f_1^q(x,\mathbf{k}_\perp)$ g_1^q $f_{1T}^{\perp q}$ g_{1T}^q

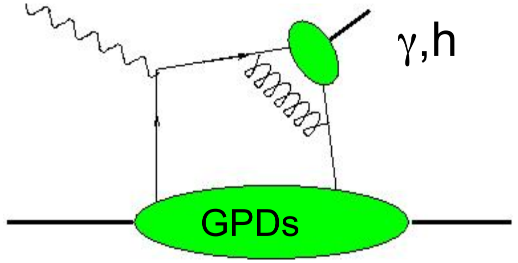
h_1^q $h_{1T}^{\perp q}$ $h_{1L}^{\perp q}$ $h_1^{\perp q}$

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$



Hard exclusive processes and spatial distributions of partons

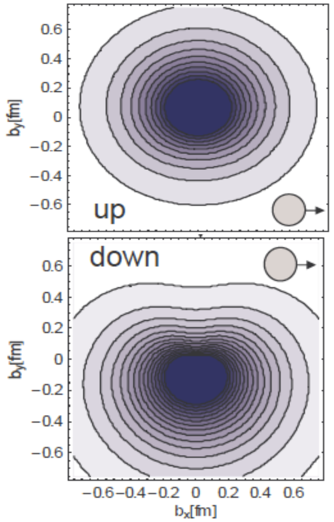




$H^q(x,\xi,t)$ $\tilde{H}^q$ E^q $\tilde{E}^q$

H_T^q $\tilde{H}_T^q$ E_T^q $\tilde{E}_T^q$

	U	L	T
U	H		$\mathcal{E}_T$
L		$\widetilde{H}$	
T	E		$H_T, \widetilde{H}_T$

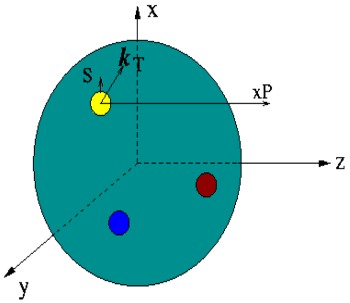


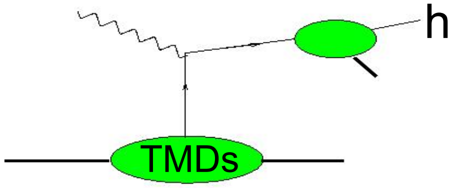
(QCDSF)

Wide kinematic coverage of large acceptance detectors allows studies of exclusive (GPDs) and semi-inclusive (TMDs) processes providing complementary information on transverse structure of nucleon

3D structure of the nucleon

Semi-Inclusive processes and transverse momentum distributions

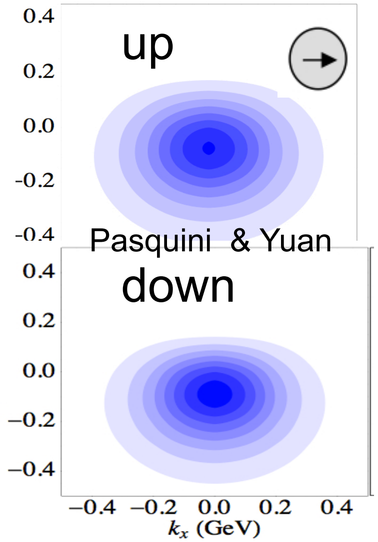




$f_1^q(x,\mathbf{k}_\perp)$ g_1^q $f_{1T}^{\perp q}$ g_{1T}^q

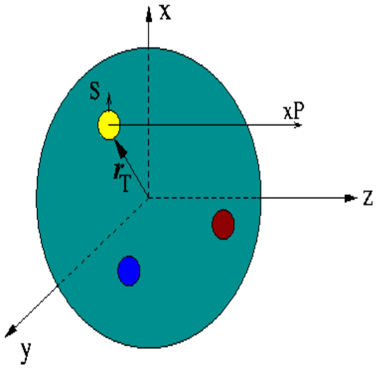
h_1^q $h_{1T}^{\perp q}$ $h_{1L}^{\perp q}$ $h_1^{\perp q}$

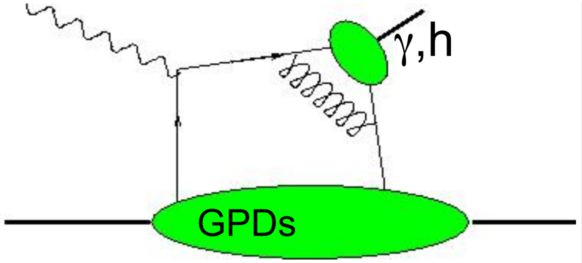
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$



Pasquini & Yuan

Hard exclusive processes and spatial distributions of partons

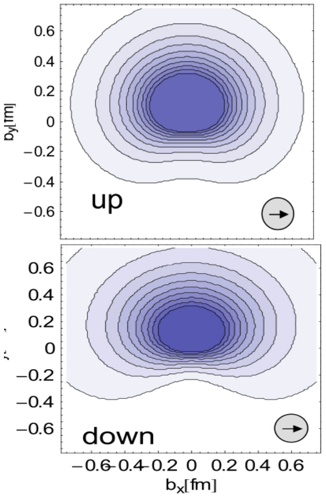




$H^q(x,\xi,t)$ $\tilde{H}^q$ E^q $\tilde{E}^q$

H_T^q $\tilde{H}_T^q$ E_T^q $\tilde{E}_T^q$

	U	L	T
U	H		$\mathcal{E}_T$
L		$\widetilde{H}$	
T	E		$H_T, \widetilde{H}_T$



(QCDSF)

Wide kinematic coverage of large acceptance detectors allows studies of exclusive (GPDs) and semi-inclusive (TMDs) processes providing complementary information on transverse structure of nucleon

Bessel Weighted Asymmetries

(Leonard Gamberg- DIS2011)

- Propose generalize Bessel Weights-”BW”
- BW procedure has advantages
- Introduces a free parameter $\mathcal{B}_T\ [\mathrm{GeV}^{-1}]$ that is Fourier conjugate to $\boldsymbol{P}_{h\perp}$

$$\mathcal{W}_{\mathrm{Sivers}} = \frac{|\boldsymbol{P}_{h\perp}|}{M}\sin(\phi_h - \phi_S)$$

$$A_{UT}^{\frac{|P_{h\perp}|}{z_h M}\sin(\phi_h-\phi_s)} = -2\frac{\sum_a e_a^2\, f_{1T}^{\perp(1)}(x)\, D_1^{a(0)}(z)}{\sum_a e_a^2\, f_1^{a(0)}(x)\, D_1^{a(0)}(z)}$$

Undefined w/o regularization to subtract infinite contribution at large transverse momentum

Bacchetta et al. JHEP 08

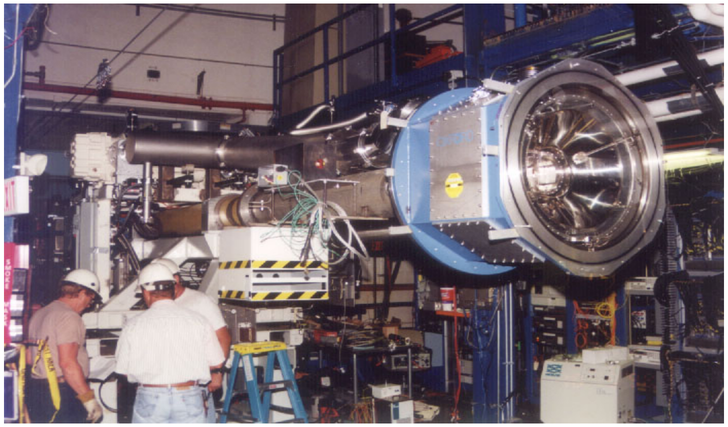
$$w_1 = 2J_1(|\boldsymbol{P}_{h\perp}|\mathcal{B}_T)/zM\mathcal{B}_T$$

$$A_{UT}^{\frac{2J_1(|\boldsymbol{P}_{h\perp}|\mathcal{B}_T)}{zM\mathcal{B}_T}\sin(\phi_h-\phi_s)} = -2\frac{\sum_a e_a^2\, \tilde{f}_{1T}^{\perp(1)a}(x, z^2\mathcal{B}_T^2)\, \tilde{D}_1^a(z,\mathcal{B}_T^2)}{\sum_a e_a^2\, \tilde{f}_1^a(x, z^2\mathcal{B}_T^2)\, \tilde{D}_1^a(z,\mathcal{B}_T^2)}$$

$\tilde{f}_1,\ \tilde{f}_{1T}^{\perp(1)}$, and $\tilde{D}_1$ are Fourier Transf. of TMDs/FFs

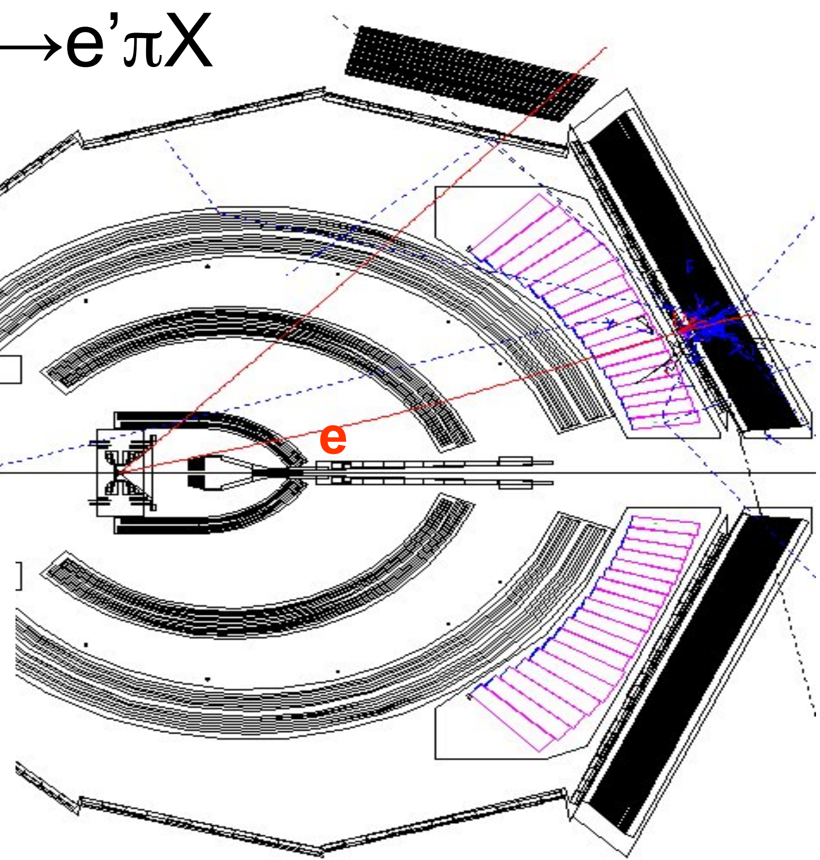
Provide access to k_T-dependence of TMDs

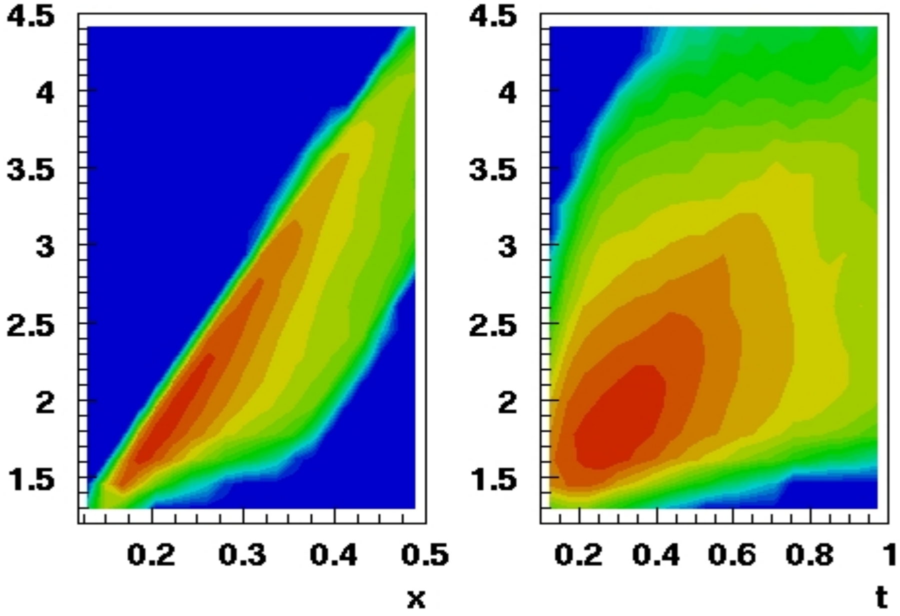
CLAS configuration with longitudinally pol. target



Longitudinally polarized target

ep→e’πX



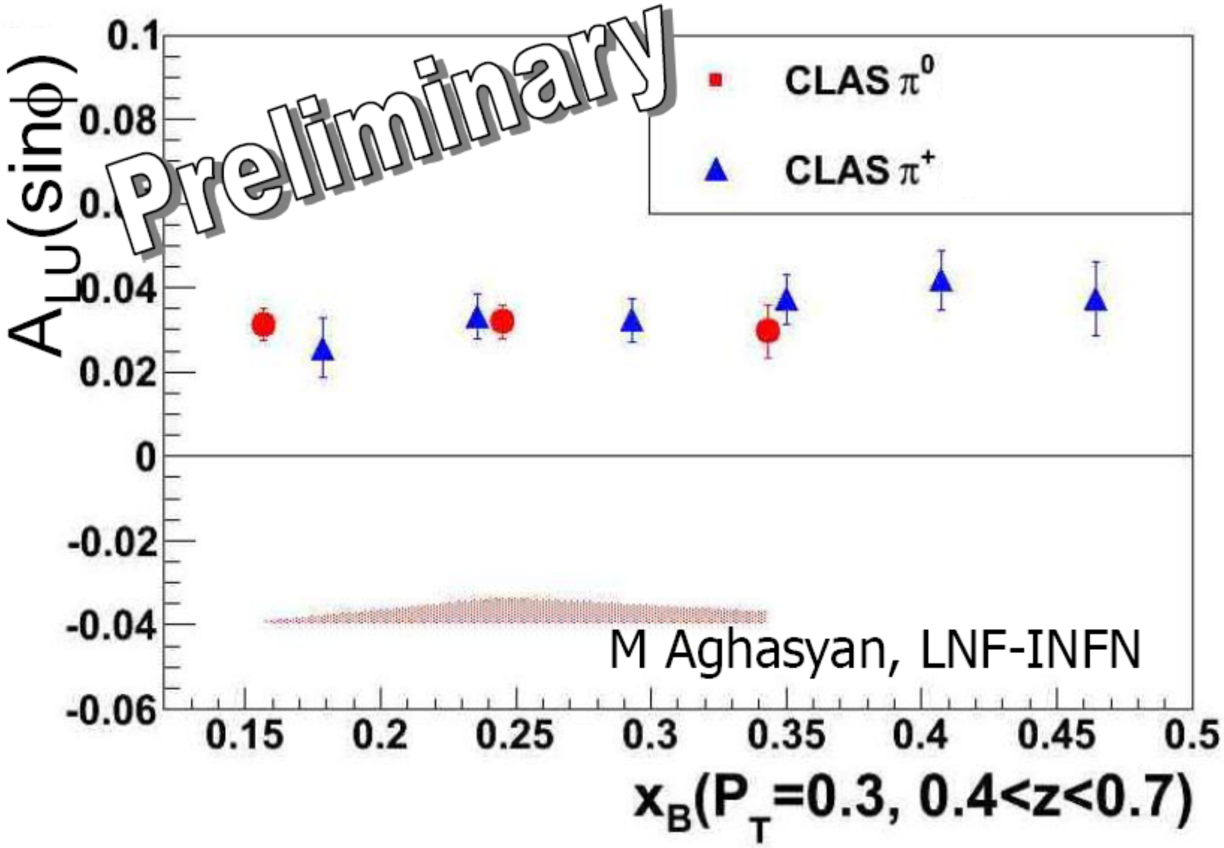


- **Polarizations:**
  - **Beam: ~70%**
  - **NH3 proton ~70%**
- **Target position -55cm**
- **Torus +/-2250**
- **Beam energy ~5.7 GeV**

Beam SSA: A_{LU} from CLAS @ JLab

$$A_{UL}^{\sin\phi} \sim g^{\perp} D_1(z)$$

Photon Sivers Effect Afanasev & Carlson, Metz & Schlegel



$$A_{LU}^{\sin\phi} \sim h_1^{\perp}(x) E(z)$$

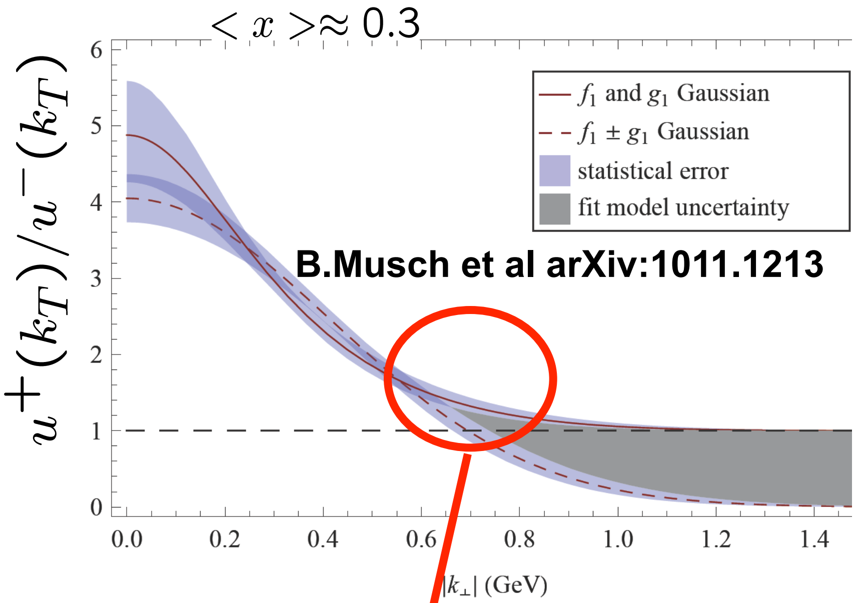
Beam SSA from initial distribution (Boer-Mulders TMD) F.Yuan using $h_1^{\perp}$ from MIT bag model

$$A_{LU}^{\sin\phi} \sim e(x) H_1^{\perp}(z)$$

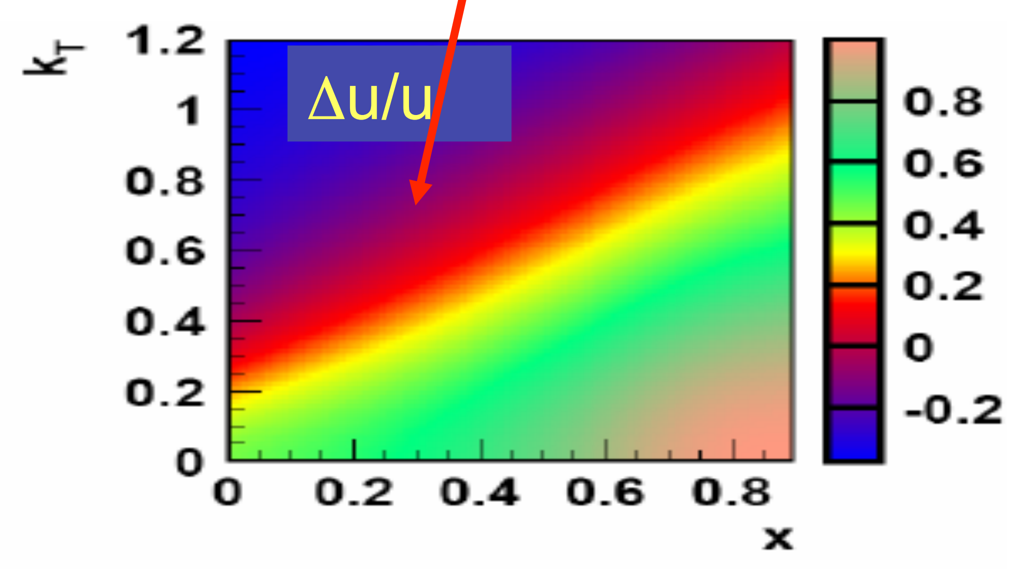
Beam SSA from hadronization (Collins effect) by Schweitzer et al.

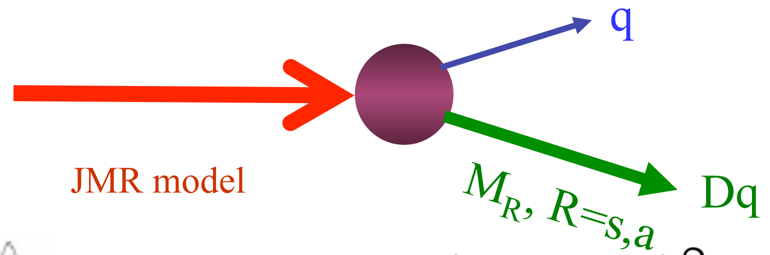
No leading twist contributions: provides access to quark-gluon correlations

Quark distributions at large k_T: models



B.Musch et al arXiv:1011.1213





JMR model

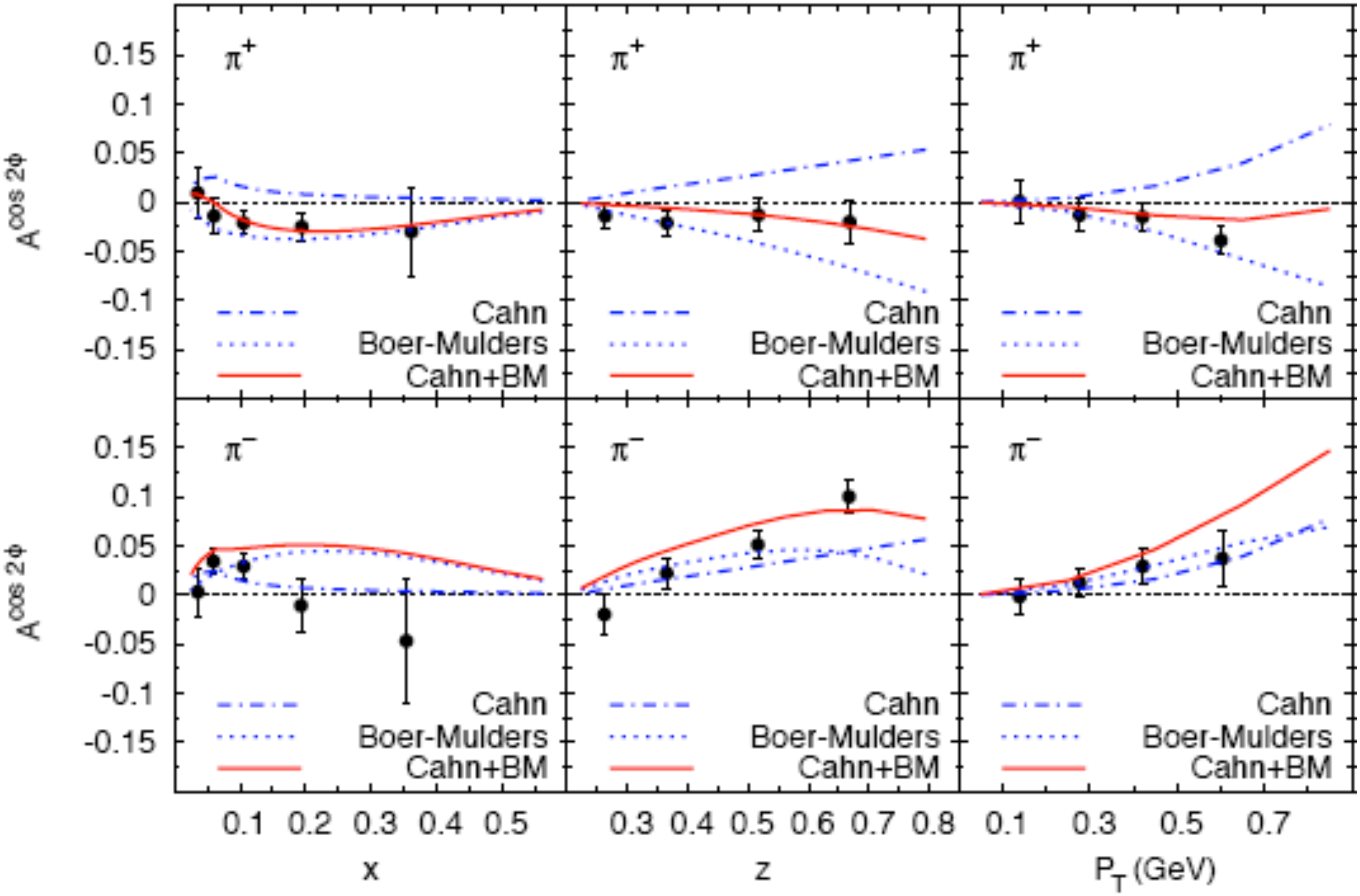
$$u^+(x,\mathbf{k}_T^2) \propto \frac{(xM+m)^2}{(\mathbf{k}_T^2+\lambda_R^2)^{2\alpha}},$$

$$u^-(x,\mathbf{k}_T^2) \propto \frac{\boxed{\mathbf{k}_T^2}}{(\mathbf{k}_T^2+\lambda_R^2)^{2\alpha}},$$

Sign change of Δu/u consistent between lattice and diquark model

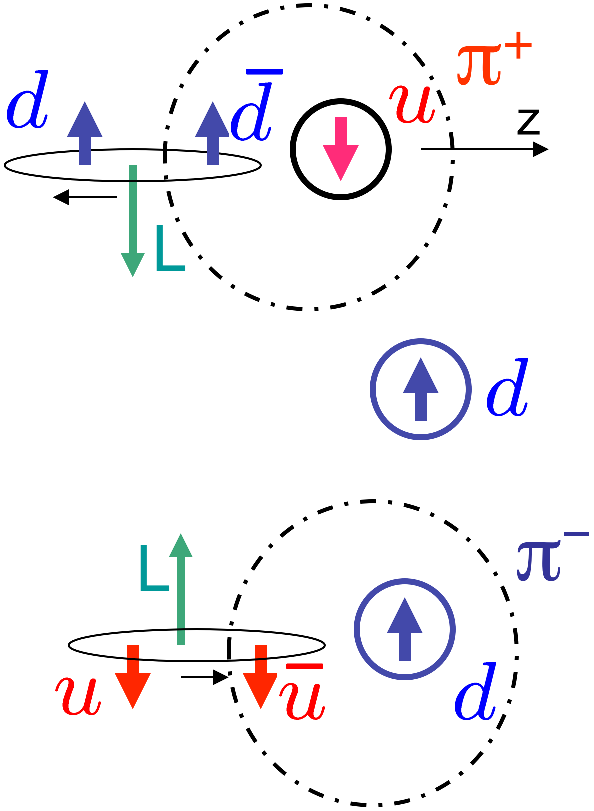
Flavor-dependent azimuthal modulations in unpolarized SIDIS cross section at HERMES

Marco Contalbrigo



Collins effect

Simple string fragmentation (Artru model)



Leading pion out of page ($\bar{d}$ - direction)

$$h_1 H_1^{\perp u\rightarrow\pi^+}$$

d kicked in the opposite to the leading pion(into the page)

Sub-leading pion opposite to leading (double kick into the page)

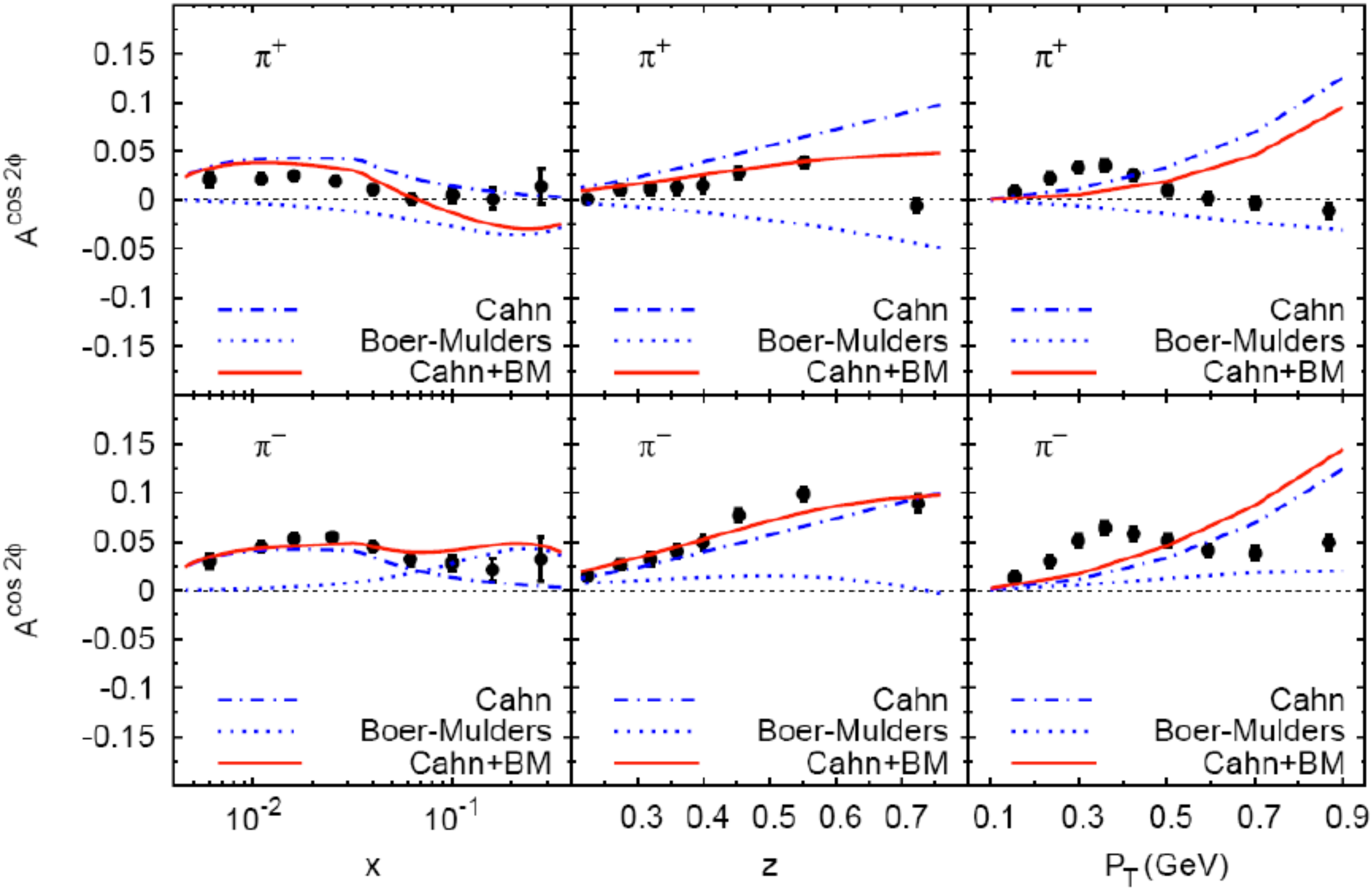
$$H_1^{\perp u\rightarrow\pi^-} > H_1^{\perp u\rightarrow\pi^+}$$

If unfavored Collins fragmentation dominates measured π- vs π+, why K- vs K+ is different?

Boer-Mulders function extraction by:

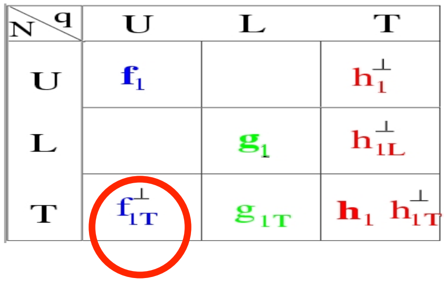
Barone, Melis and Prokudin Phys. Rev. D**81** (2010) 114026

2008 COMPASS results !



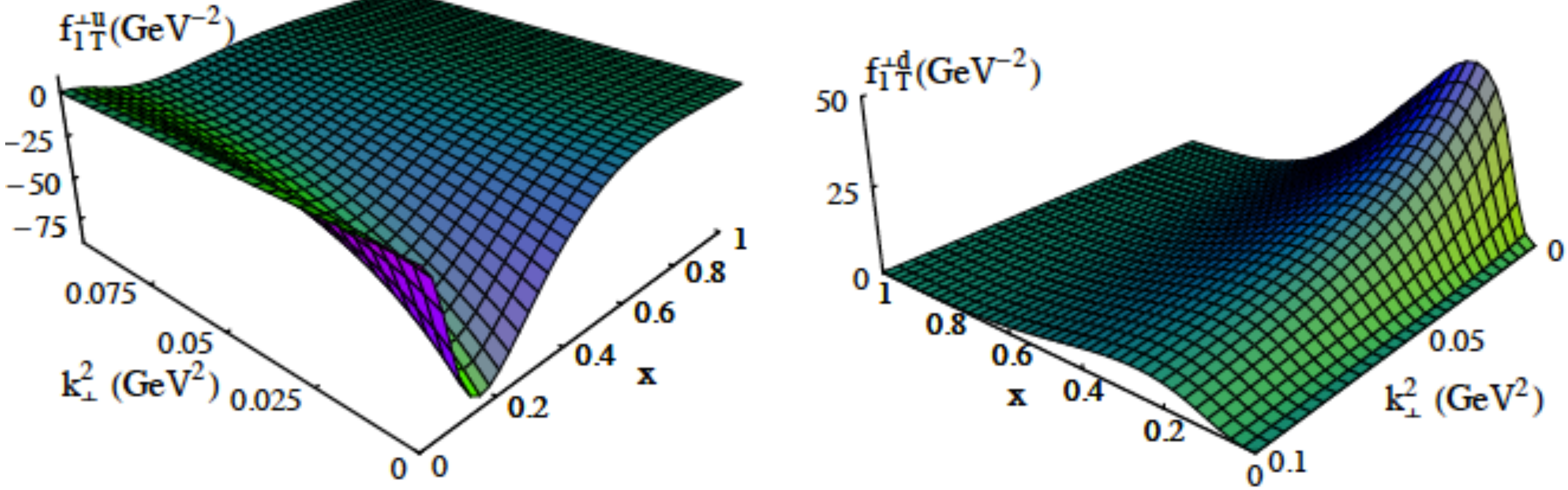
SIDIS ($\gamma^* p \rightarrow \pi X$) : Transversely polarized target

- Azimuthal moments in pion production in SIDIS
  - $\sin(\phi - \phi_S)$ (Sivers function $f_{1T}^{\perp}$) and relation with GPDs
  - $\sin(\phi + \phi_S)$ (Collins function $H_1^{\perp}$ and transversity h_1)
  - $\sin(3\phi - \phi_S)$ (Collins function $H_1^{\perp}$ and pretzelosity $h_{1T}^{\perp}$)



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 $h_{1T}^\perp$

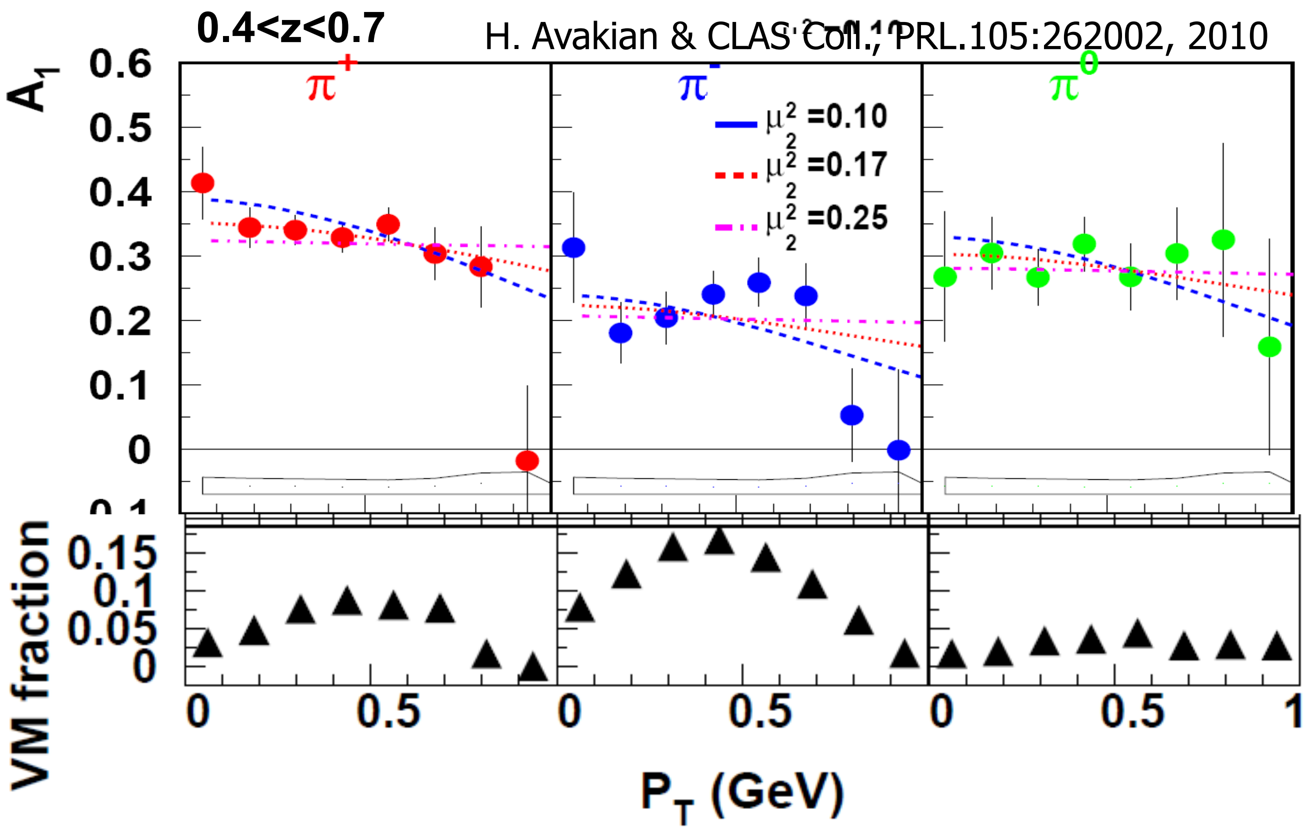
Pasquini and Yuan, Phys.Rev.D81:114013,2010



A_1 – P_T dependence

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 $h_{1T}^\perp$

$$A_1(x,z,P_T) = A_1(x,z)\frac{\langle P_T^{2,unp}\rangle}{\langle P_T^{2,pol}\rangle}\exp(-P_T^2/\langle P_T^{2,pol}\rangle - P_T^2/\langle P_T^{2,unp}\rangle)$$



H. Avakian & CLAS Coll., PRL.105:262002, 2010

M. Anselmino et al PRD74:074015, 2006

μ_0^2=0.25GeV^2
μ_D^2=0.2GeV^2

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

$$g_1^q(x,k_T) = g_1(x)\frac{1}{\pi\mu_2^2}\exp\left(-\frac{k_T^2}{\mu_2^2}\right)$$

$$< P_T^2(z) >= z^2\mu_{0/2}^2 + \mu_D^2$$

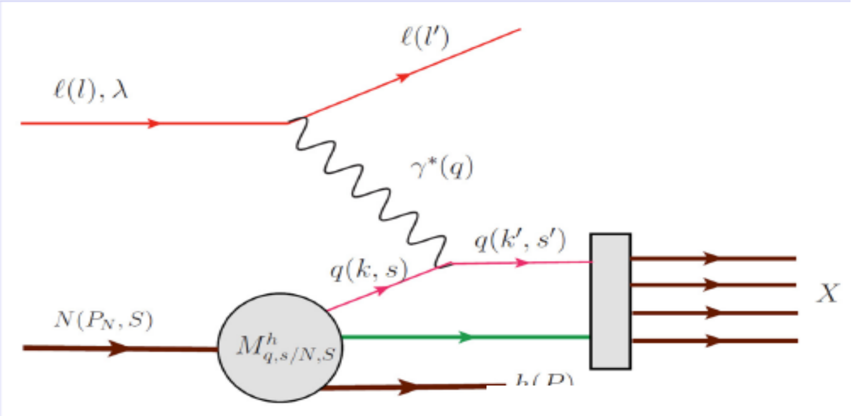
π^+ A_1 suggests broader k_T distributions for f_1 than for g_1
π^- A_1 may require non-Gaussian k_T-dependence for different helicities and/or flavors

SIDIS in target fragmentation region

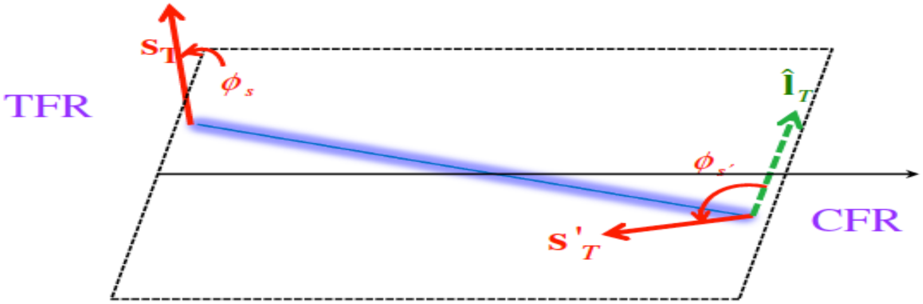
Aram Kotzinian

- TFR (based on M.Anselmino, V.Barone and AK, **arXiv:1102.4214;** PLB 699 (2011) 108)

SIDIS: TFR



Hadronization in SIDIS



LO cross-section in TFR

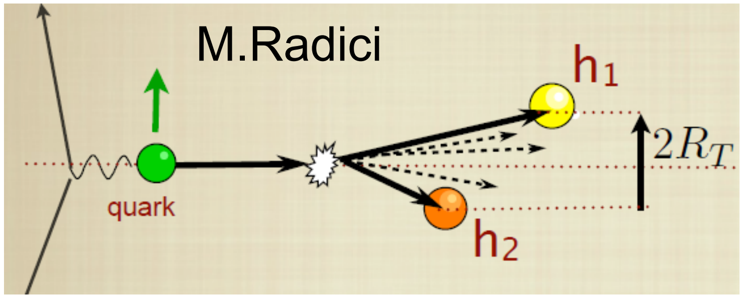
$$\frac{d\sigma^{\ell(l,\lambda)+N(P_N,S)\to\ell(l')+h(P)+X}(x_F<0)}{dx\,dQ^2\,d\phi_S\,d\zeta\,d^2P_T}=\frac{\alpha^2 x}{yQ^4}\left(1+(1-y)^2\right)\sum_q e_q^2\times$$

$$\times\left[\begin{array}{l} M\left(x,\zeta,P_T^2\right)-S_T\dfrac{P_T}{m_h}M_T^h\left(x,\zeta,P_T^2\right)\sin(\phi_h-\phi_S)+ \\ \lambda D_{ll}(y)\left(S_L\Delta M_L\left(x,\zeta,P_T^2\right)+S_T\dfrac{P_T}{m_h}\Delta M_T^h\left(x,\zeta,P_T^2\right)\cos(\phi_h-\phi_S)\right)\end{array}\right]$$

- The ideal place to test the fracture functions factorization and measure these new functions are JLab12 and EIC facilities with full coverage of phase space

HT-distributions and dihadron SIDIS

Compare single hadron and dihadron SSAs

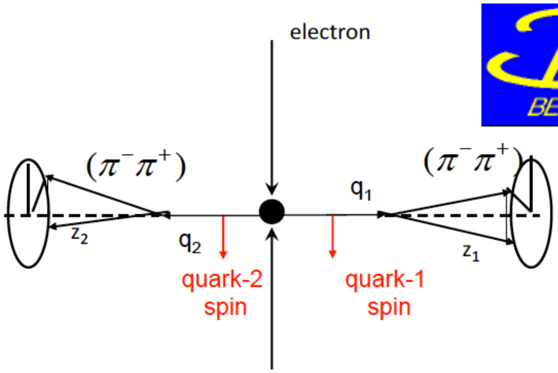


$$\frac{M}{M_h}\, x\, e(x)\, H_1^{\sphericalangle}(z,\zeta,M_h^2) + \frac{1}{z}\, f_1(x)\, \widetilde{G}^{\sphericalangle}(z,\zeta,M_h^2)$$

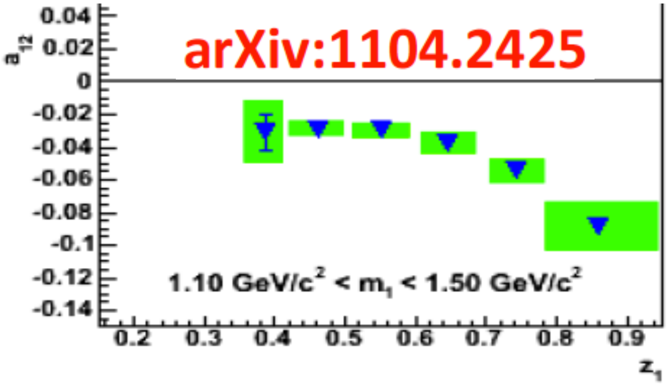
$$\frac{M}{M_h}\, x\, h_L(x)\, H_1^{\sphericalangle}(z,\zeta,M_h^2) + \frac{1}{z}\, g_1(x)\, \widetilde{G}^{\sphericalangle}(z,\zeta,M_h^2)$$

Only 2 terms with common unknown HT G~ term!

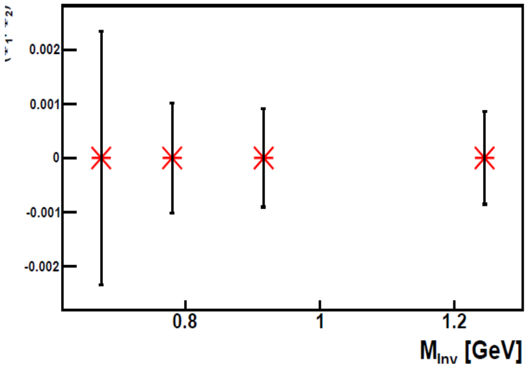
Aurore Courtoy/Anselm Voosen - Spin session



BELLE



Projections for
(π^+K^-) $(K^+\pi^-)$ for 580 fb^{-1}



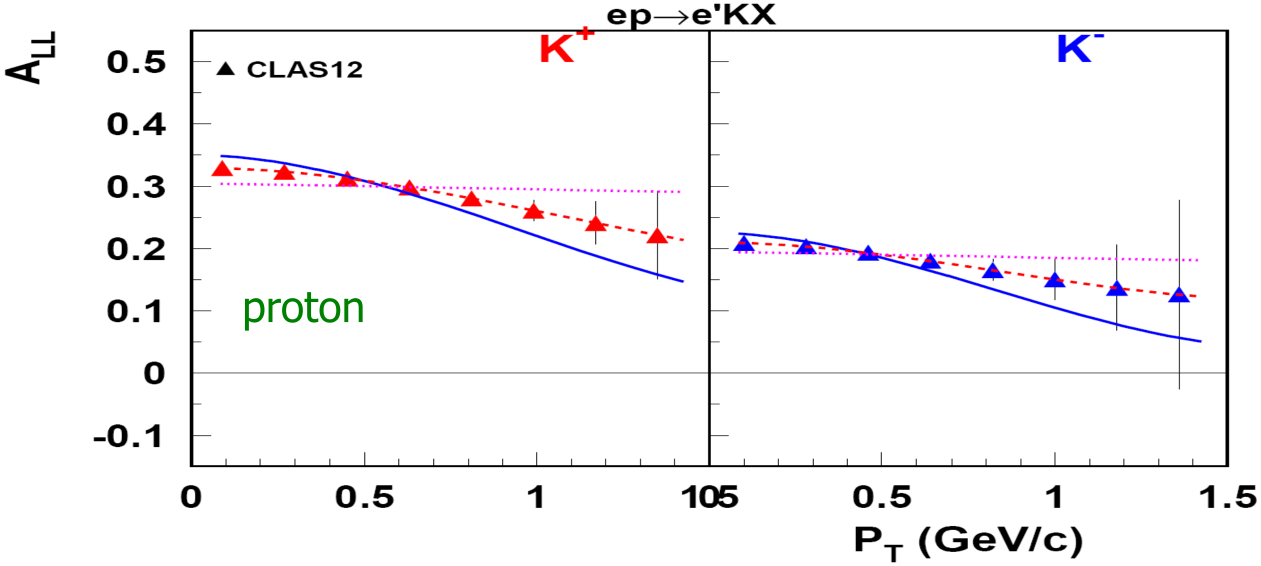
- Higher twists in dihadron SIDIS collinear (no problem with factorization)
- Bell can measure K+π- dihadron fragmentation functions

Transverse momentum distributions of partons

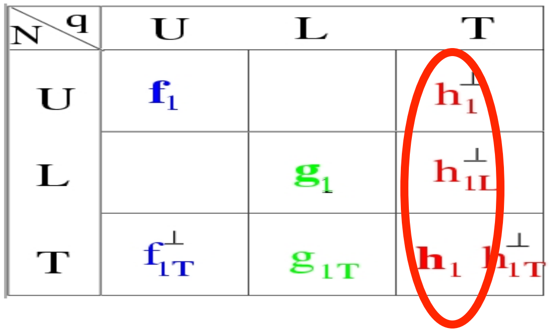
NJL model H. Matevosyan et al. arXiv:1011.1052 [hep-ph]

$$\langle P_T^2\rangle \approx z^2\langle k_\perp^2\rangle + \langle p_\perp^2\rangle$$

Transverse momentum distributions in hadronization may be flavor dependent
=> measurements of different final state hadrons required



Collins effect: from asymmetries to distributions



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 $h_{1T}^\perp$

need $H_1^\perp$

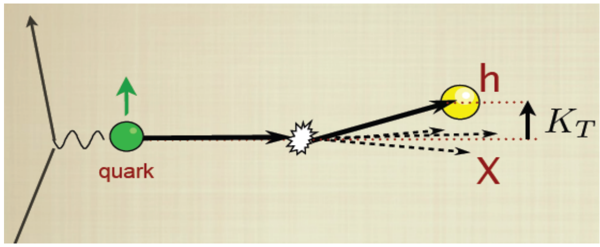
$$F \equiv \sigma_{UL}^{\sin 2\phi}, \sigma_{UU}^{\cos 2\phi}, \ldots.$$

$$\frac{H_1^{u/K+} - H_1^{u/K-}}{H_1^{u/\pi+} - H_1^{u/\pi-}} = \frac{15}{4}\frac{F_p^{K+} - F_p^{K-}}{3(F_p^{\pi+} - F_p^{\pi-}) + (F_d^{\pi+} - F_d^{\pi-})}$$

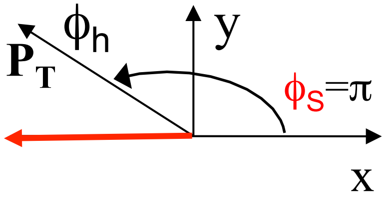
Combined analysis of Collins fragmentation asymmetries from proton and deuteron and for π and K may provide independent to e^+e^- (BELLE/BABAR) information on the underlying Collins function.

Chiral odd HT-distribution

How can we separate the HT contributions?



$F_{LU}^{\sin\phi}$ $F_{UL}^{\sin\phi}$

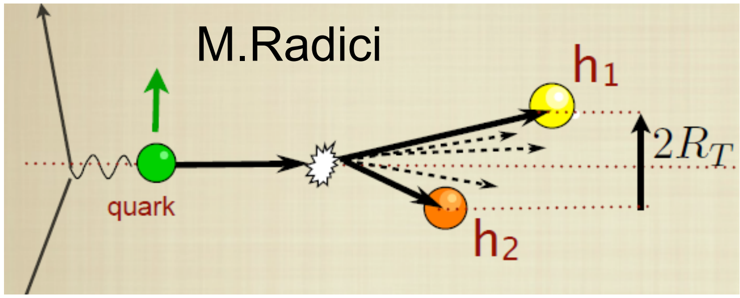


$eH_1^{\perp}$, $h_L H_1^{\perp}$ $\sin\phi_h$

↑

HT function related to force on the quark. M.Burkardt (2008)

Compare single hadron and dihadron SSAs

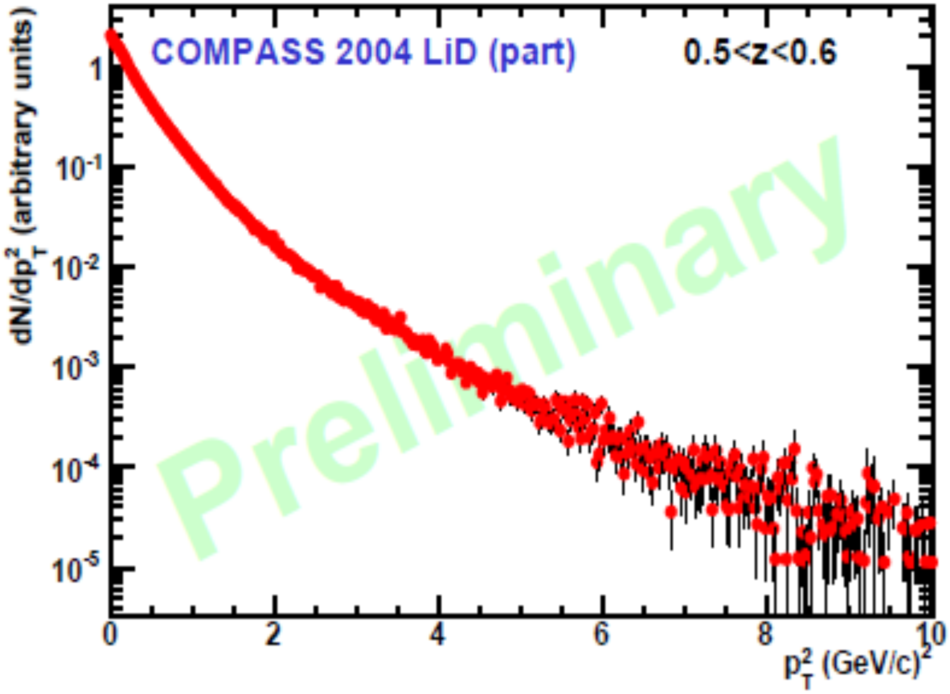

M.Radici

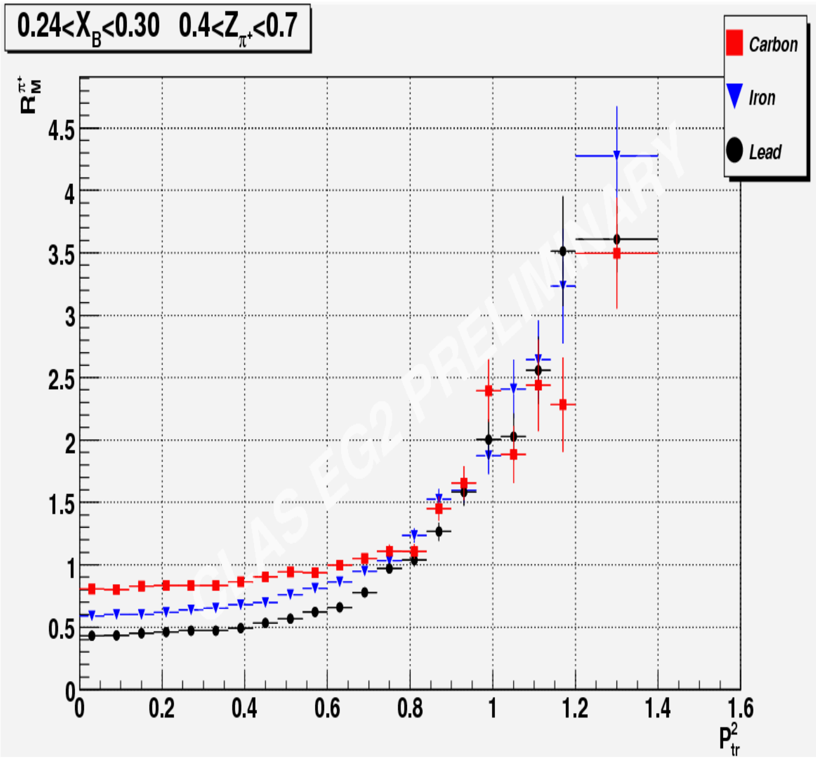
$$\frac{M}{M_h}\, x\, e(x)\, H_1^{\sphericalangle}(z,\zeta,M_h^2) + \frac{1}{z} f_1(x)\, \tilde{G}^{\sphericalangle}(z,\zeta,M_h^2)$$

$$\frac{M}{M_h}\, x\, h_L(x)\, H_1^{\sphericalangle}(z,\zeta,M_h^2) + \frac{1}{z} g_1(x)\, \tilde{G}^{\sphericalangle}(z,\zeta,M_h^2)$$

Only 2 terms with common unknown HT G~ term!

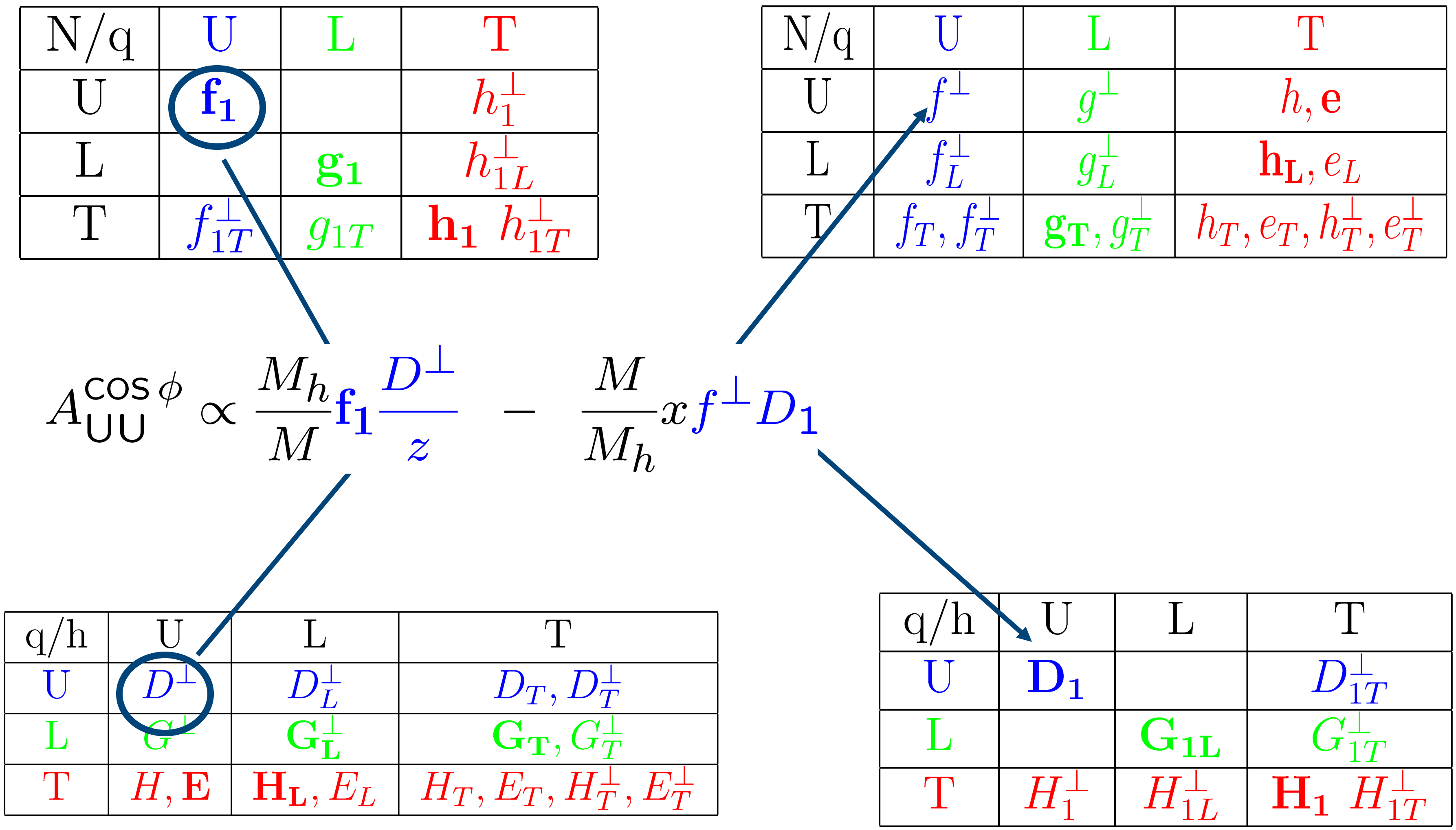
Nuclear broadening Hadronic PT-distriutions





Large PT may have significant nuclear contribution

Azimuthal moments with unpolarized target



quark polarization

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

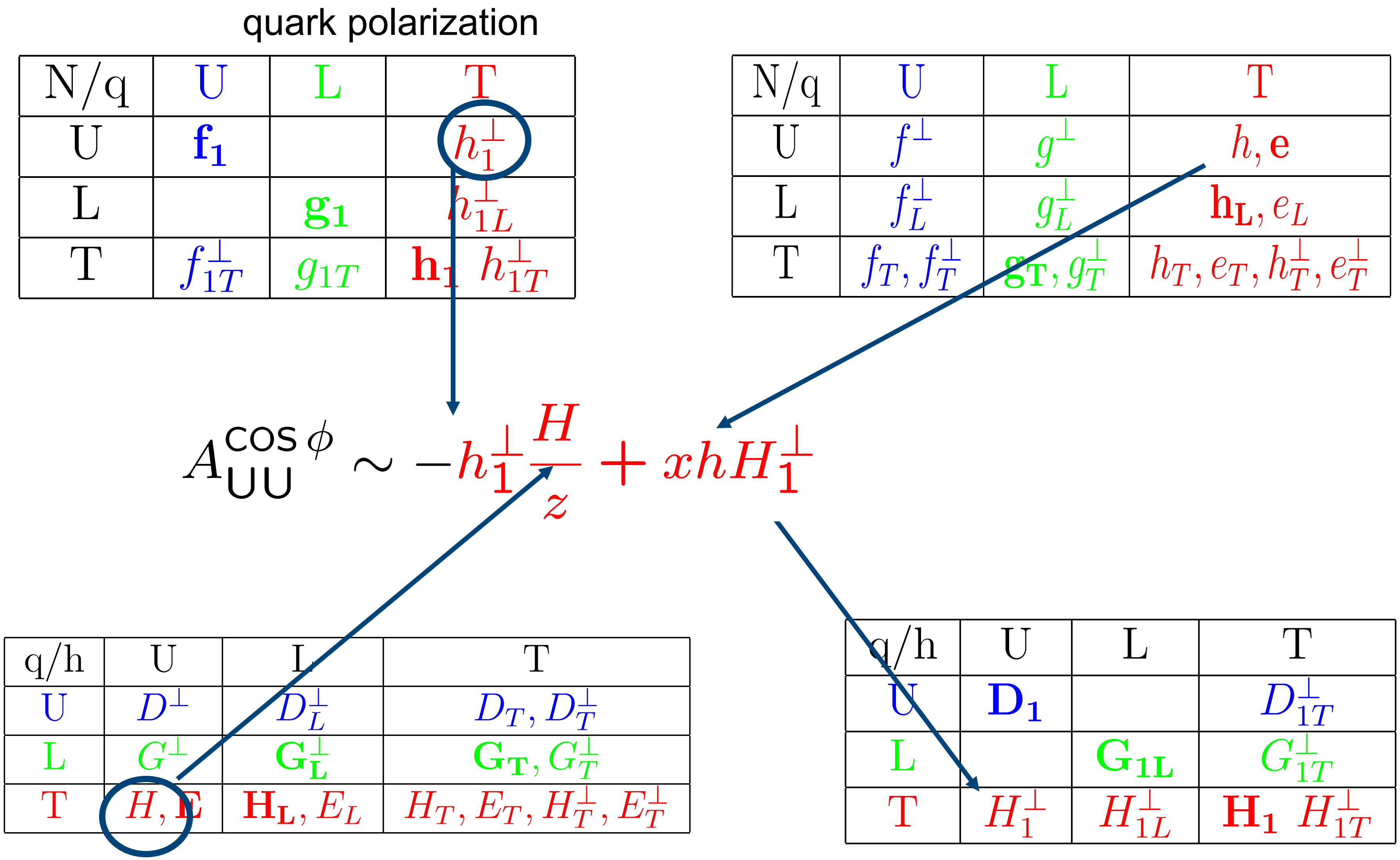
N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{\mathrm{UU}}^{\cos\phi} \propto \frac{M_h}{M}\mathbf{f_1}\frac{D^\perp}{z} - \frac{M}{M_h}x f^\perp D_1$$

q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

Azimuthal moments with unpolarized target



quark polarization

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

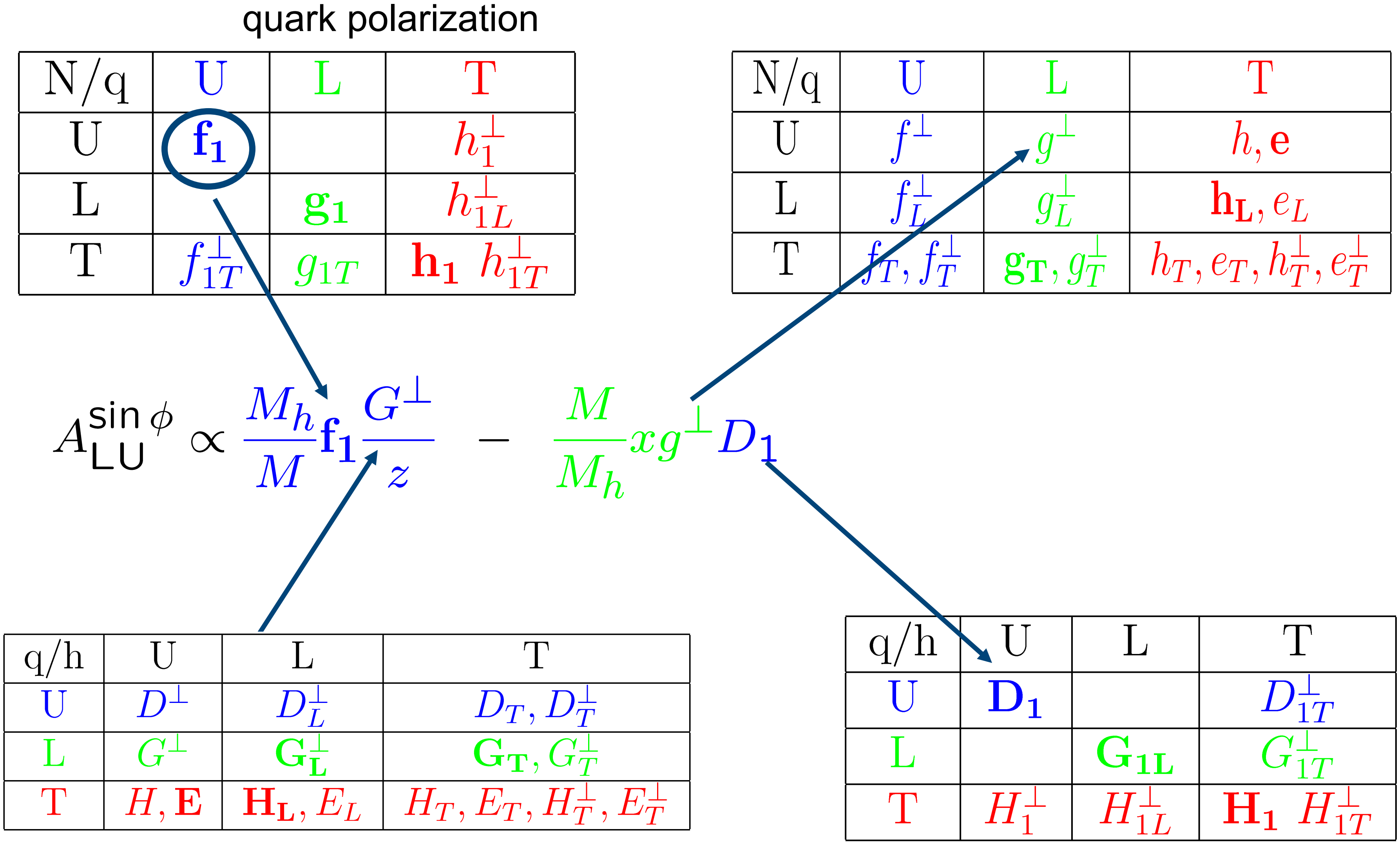
N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{UU}^{\cos\phi} \sim -h_1^\perp \frac{H}{z} + xhH_1^\perp$$

q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	H, E	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

SSA with unpolarized target



quark polarization

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

N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{LU}^{\sin\phi} \propto \frac{M_h}{M}\mathbf{f_1}\frac{G^\perp}{z} - \frac{M}{M_h} x g^\perp D_1$$

q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

SSA with unpolarized target

quark polarization

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

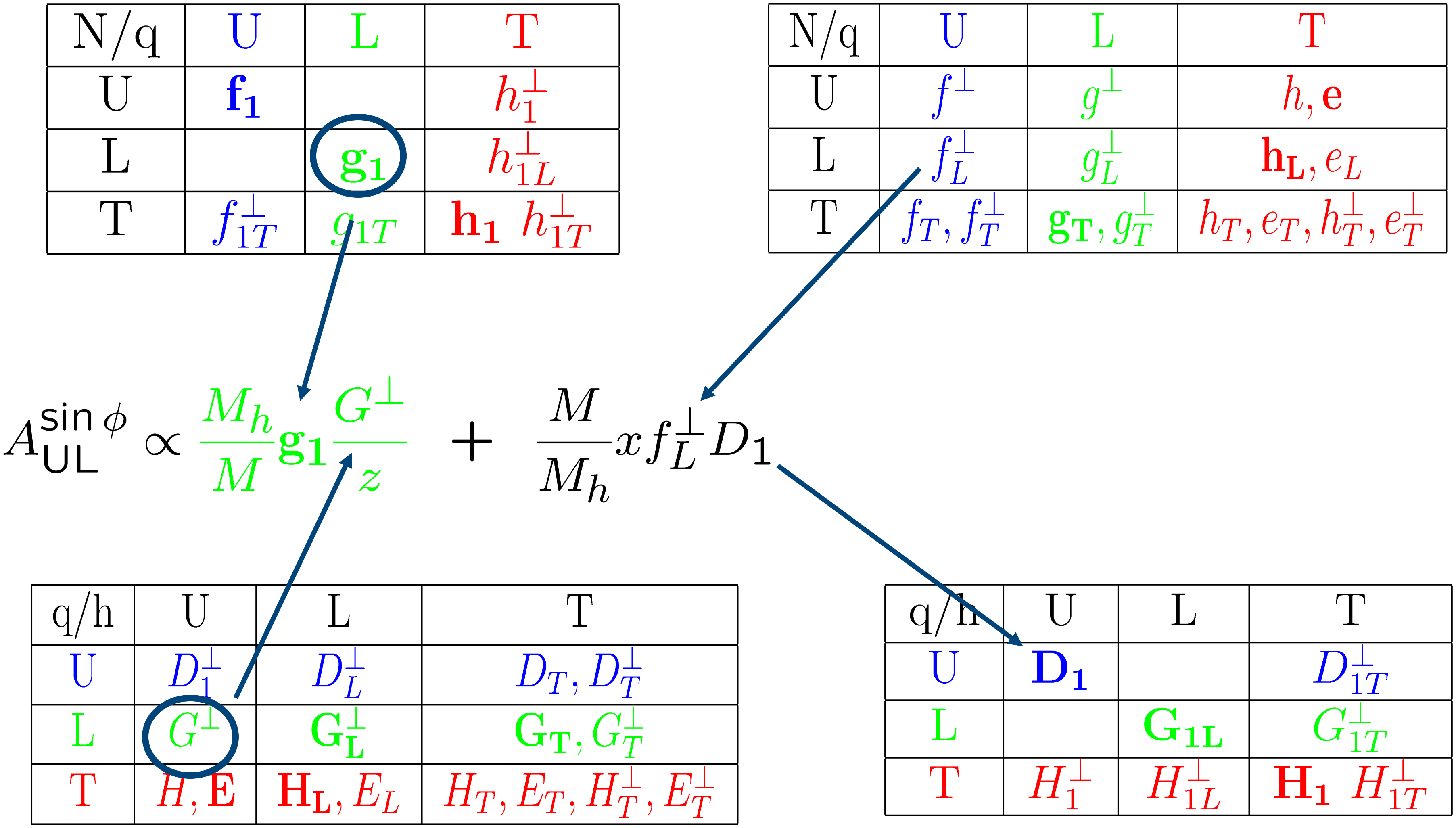
N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{\mathrm{LU}}^{\sin\phi} \sim h_1^\perp \frac{E}{z} + xeH_1^\perp$$

q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

SSA with long. polarized target



quark polarization

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

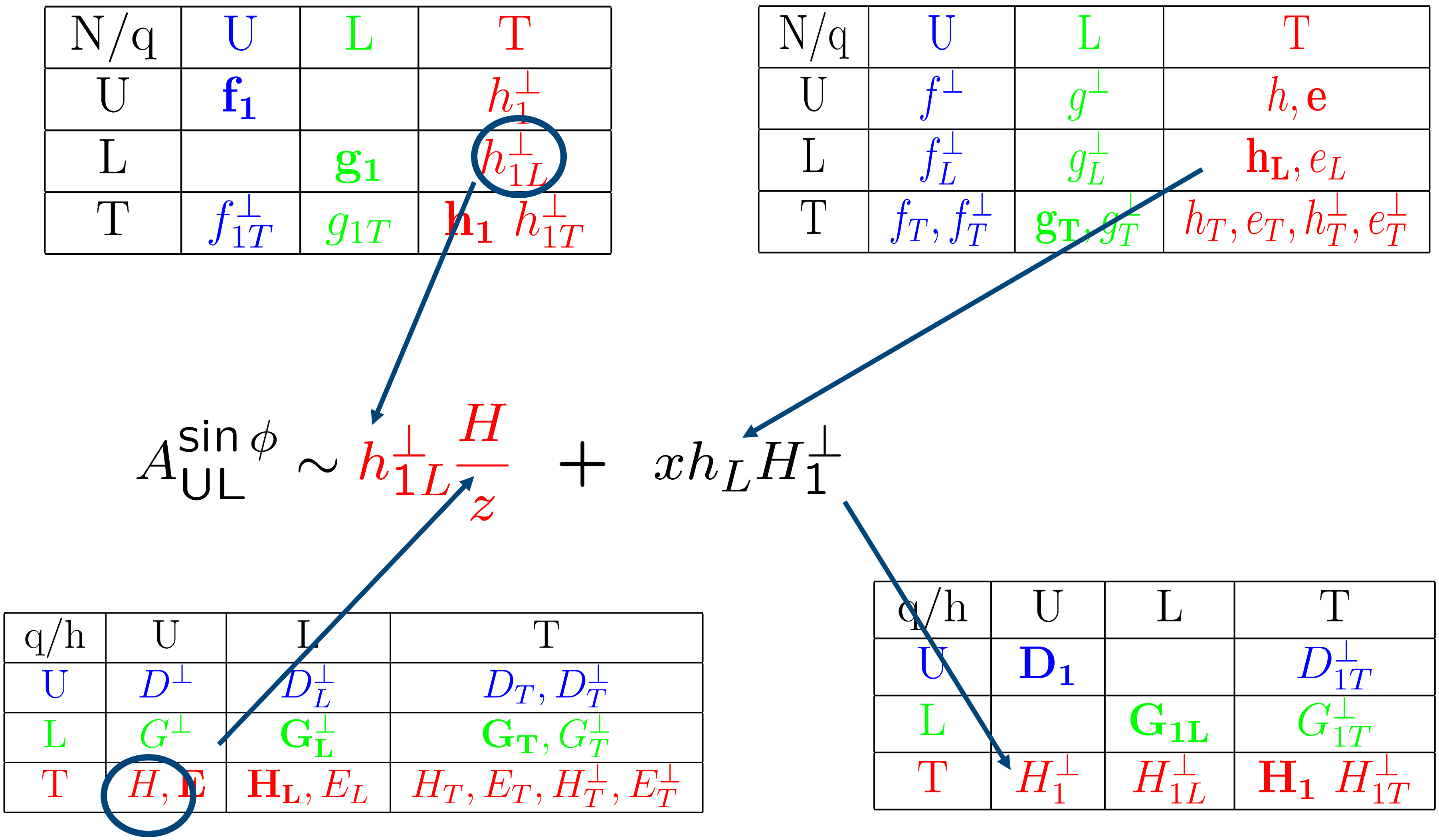
N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{\mathrm{UL}}^{\sin\phi} \propto \frac{M_h}{M}\mathbf{g_1}\frac{G^\perp}{z} + \frac{M}{M_h} x f_L^\perp D_1$$

q/h	U	L	T
U	$D_1^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G}_{\mathbf{L}}^\perp$	$\mathbf{G_T}, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

SSA with long. polarized target



quark polarization

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

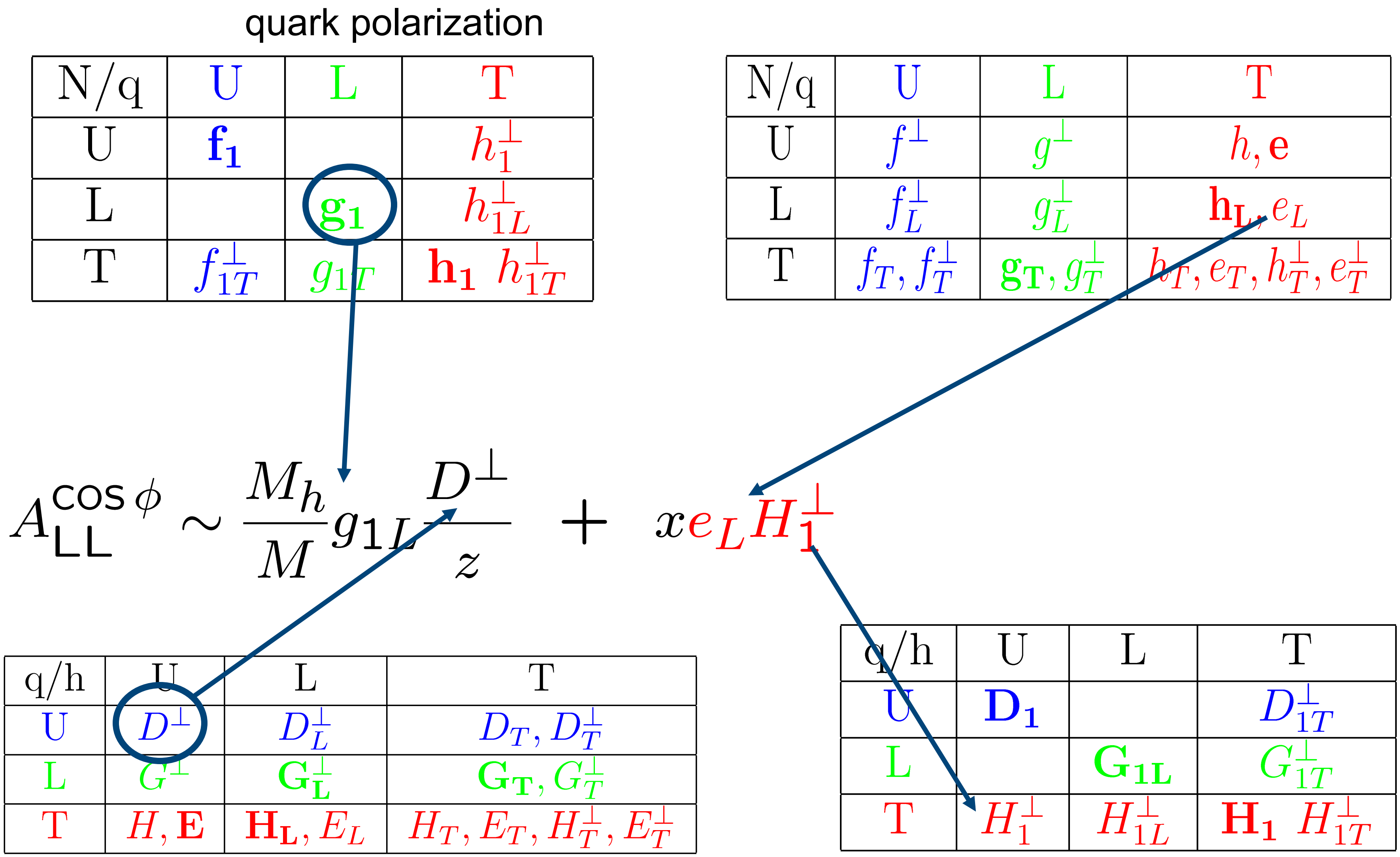
N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{\mathrm{UL}}^{\sin\phi} \sim h_{1L}^\perp \frac{H}{z} + x h_L H_1^\perp$$

q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

SSA with unpolarized target



quark polarization

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

N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{\mathrm{LL}}^{\cos\phi} \sim \frac{M_h}{M} g_{1L} \frac{D^\perp}{z} + x e_L H_1^\perp$$

q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

SSA with unpolarized target

quark polarization

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

N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

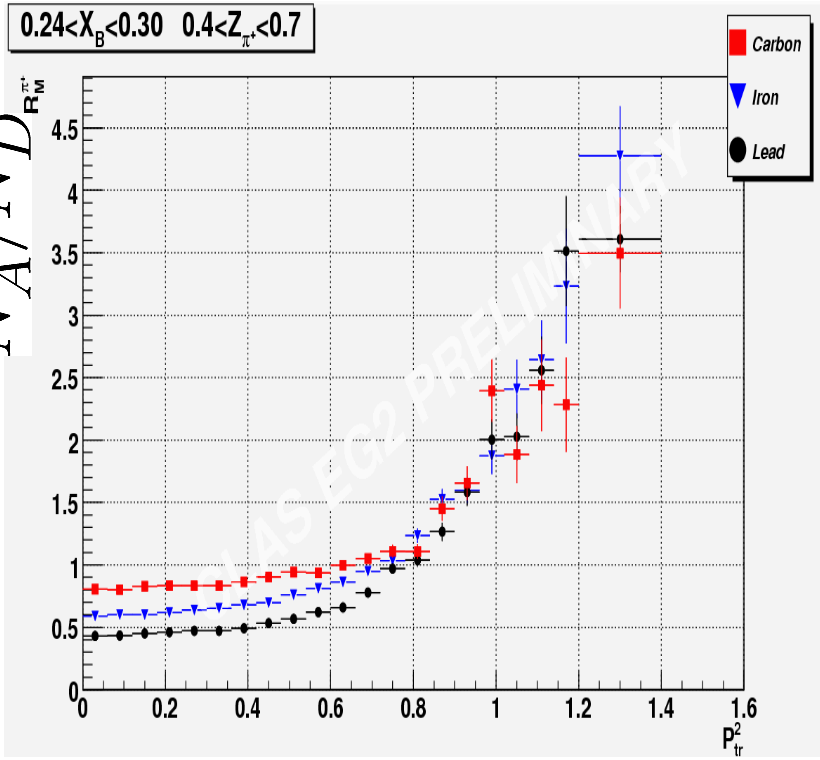
$$A_{LL}^{\cos\phi} \sim \frac{M_h}{M} h_{1L}^\perp \frac{E}{z} + x g_L^\perp D_1$$

q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

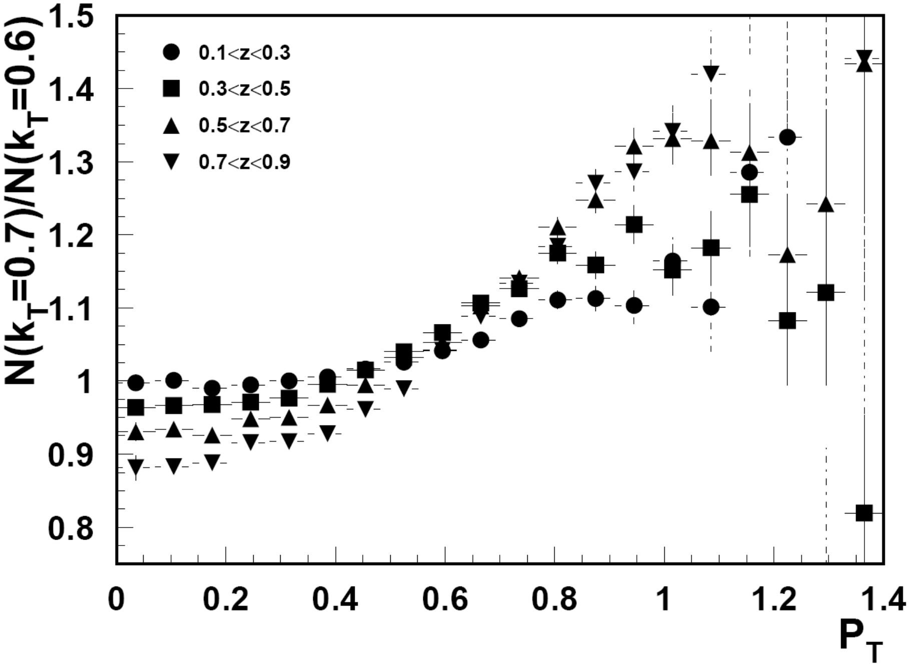
Twist-3 PDFs : “new testament”

Quark distributions at large k_T



bigger effect at large z

$P_T = p_\perp + z\, k_T$



Higher probability to find a hadron at large P_T in nuclei

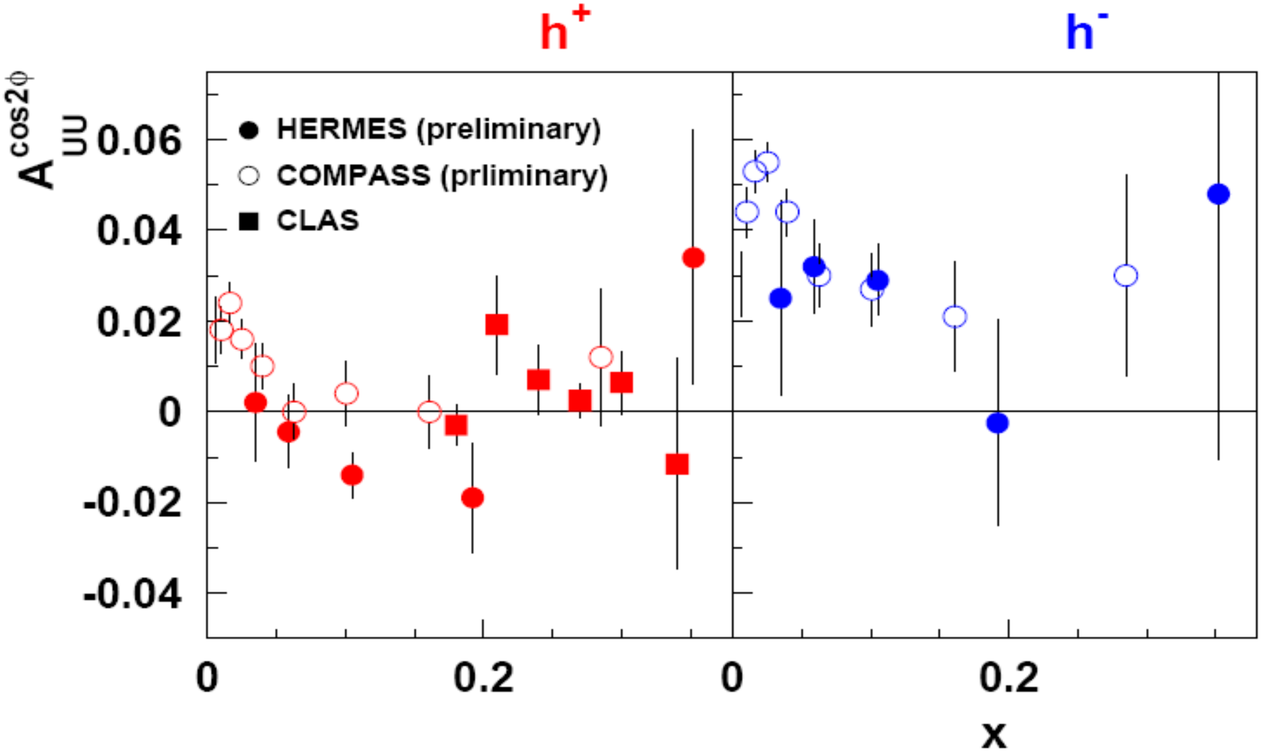
k_T-distributions may be wider in nuclei?

SIDIS (γ*p->πX) x-section at leading twist

TMD PDFs

$$\frac{d\sigma}{dxdydzd^2\vec{P}_h} = \frac{4\pi\alpha^2 s}{Q^4}[x(1-y+y^2/2)F_{UU} \longrightarrow f_1 D_1$$

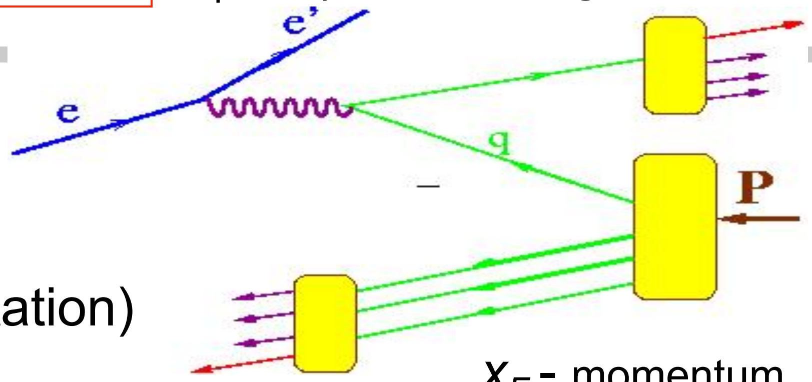
$$-x(1-y)\cos(2\phi)F_{UU}^{\cos 2\phi}] \longrightarrow h_1^\perp H_1^\perp$$



- **Measure Boer-Mulders distribution functions and probe the polarized fragmentation function**
- **Measurements from different experiments consistent**

Single hadron production in hard scattering

$x_F>0$ (current fragmentation)



$x_F<0$ (target fragmentation)

x_F - momentum in the CM frame

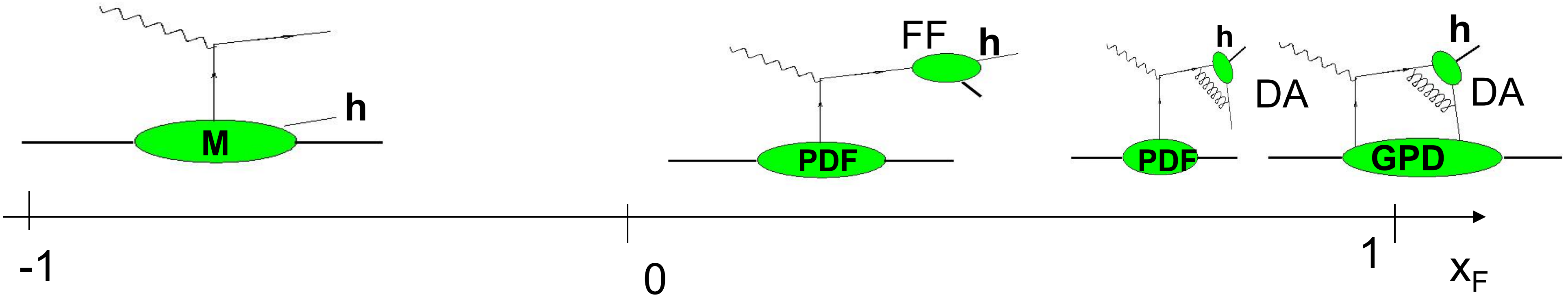
Target fragmentation

Current fragmentation

semi-inclusive

semi-exclusive

exclusive



Fracture Functions

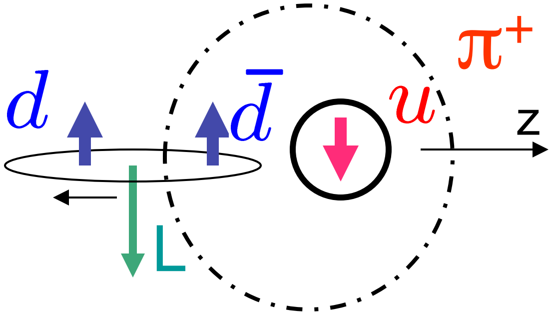
k_T-dependent PDFs

Generalized PDFs

Wide kinematic coverage of large acceptance detectors allows studies of hadronization both in the target and current fragmentation regions

Collins effect

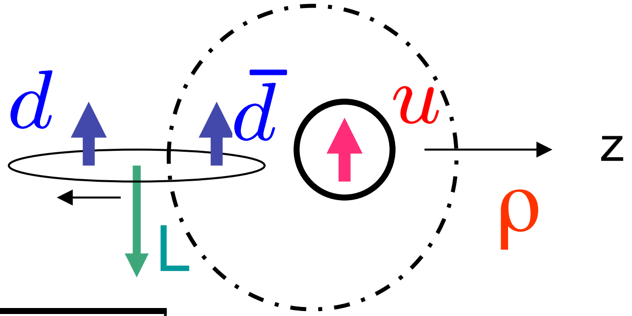
Simple string fragmentation for pions (Artru model)



leading pion out of page

$$h_1 H_1^{\perp u \to \pi}$$

ρ production may produce an opposite sign A_{UT}



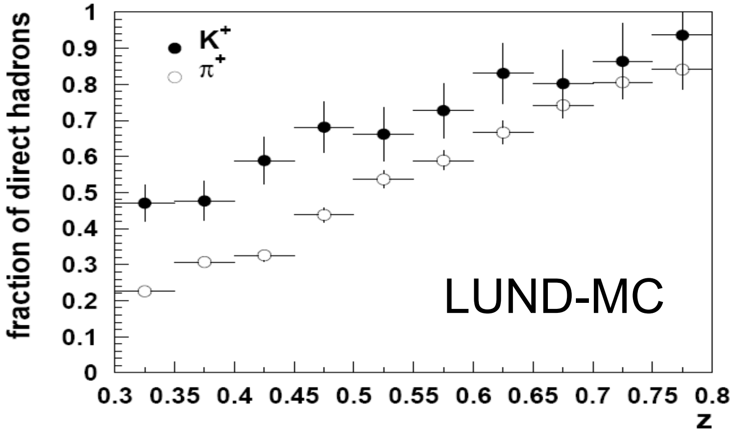
Leading ρ opposite to leading π(into page)

$$H_1^{\perp u \to \rho} \sim -\frac{1}{3} H_1^{\perp u \to \pi}$$

hep-ph/9606390

Fraction of ρ in eπX	% left from eπX asm
20%	~75%
40%	~50%

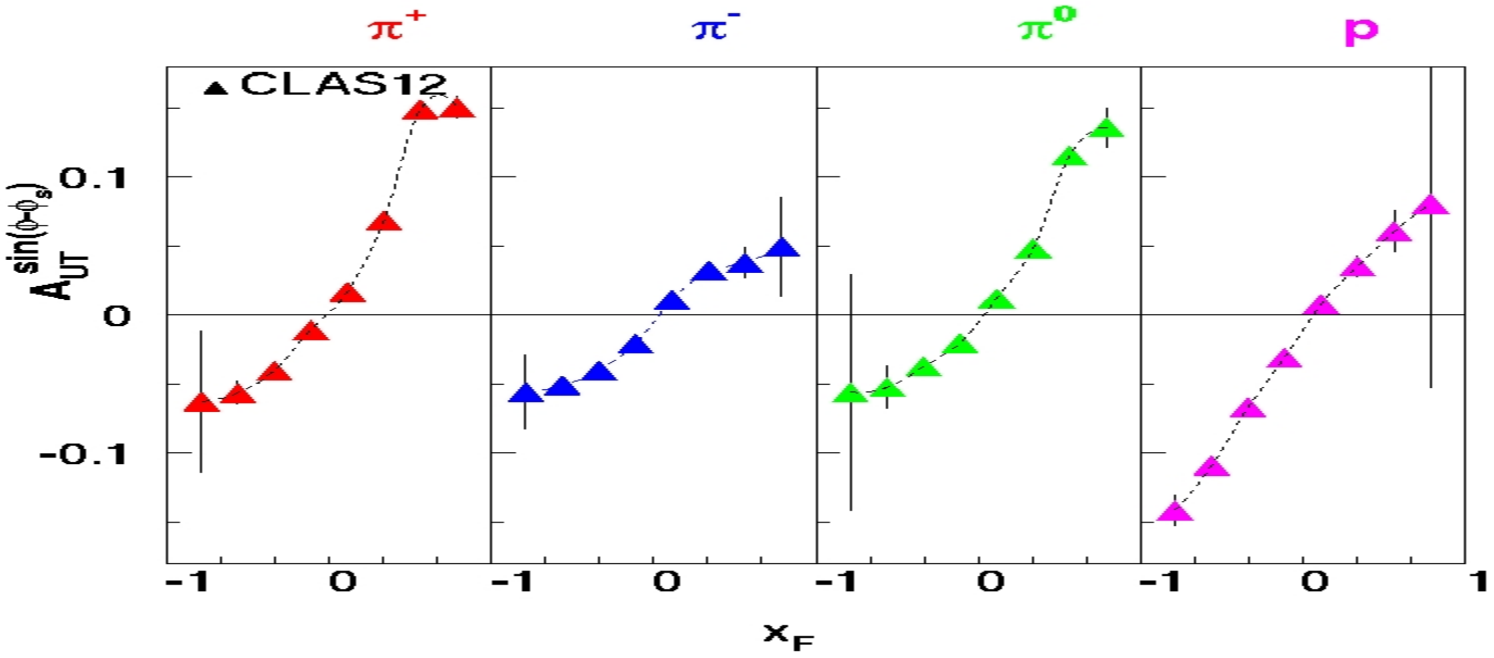
Fraction of direct kaons may be significantly higher than the fraction of direct pions.



LUND-MC

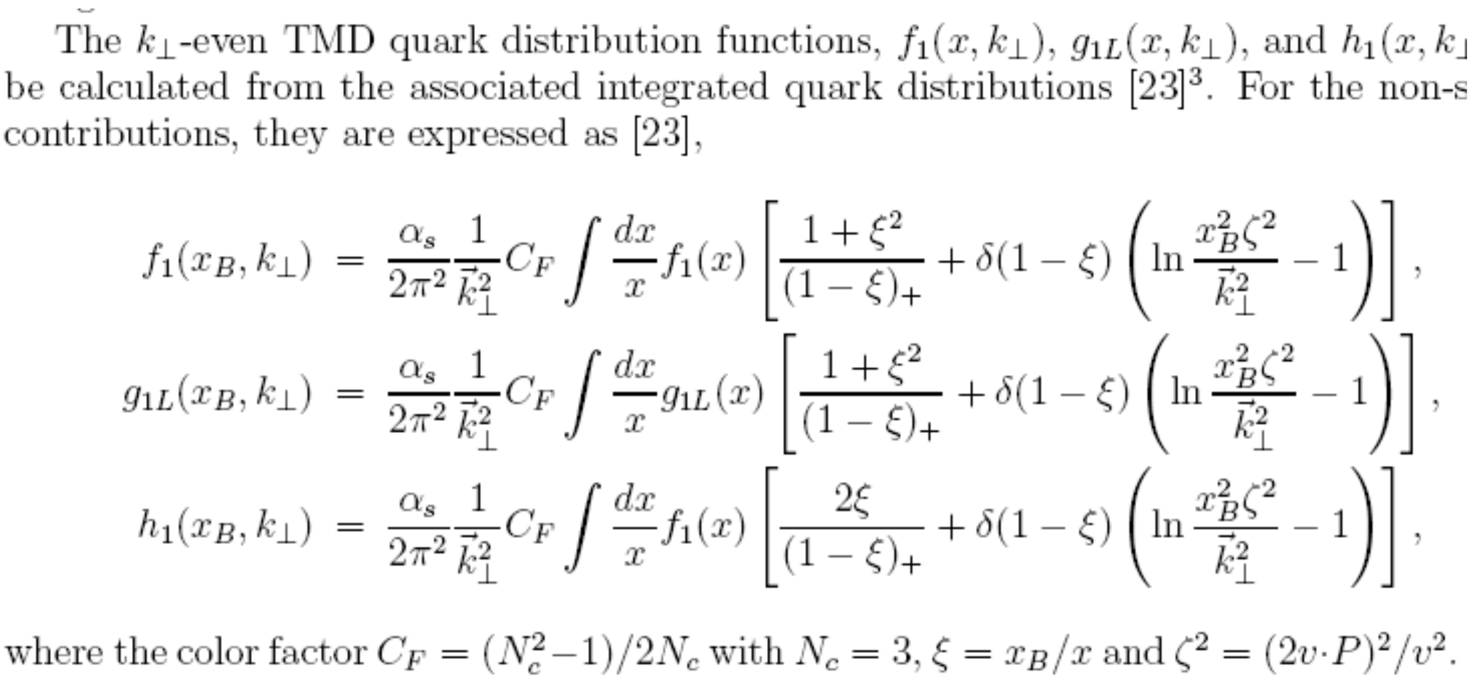
Sivers effect in the target fragmentation

A.Kotzinian



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

hep:arXiv-09092238



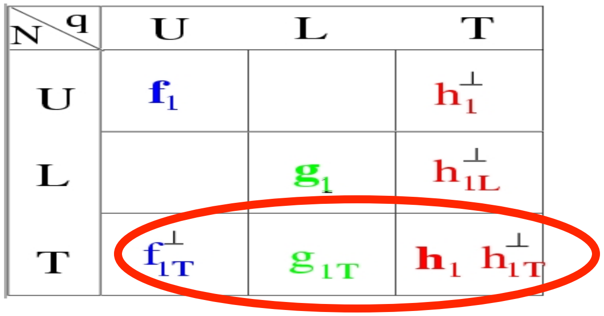
The $k_\perp$-even TMD quark distribution functions, $f_1(x, k_\perp)$, $g_{1L}(x, k_\perp)$, and $h_1(x, k$
be calculated from the associated integrated quark distributions [23]^3. For the non-s
contributions, they are expressed as [23],

$$
\begin{aligned}
f_1(x_B, k_\perp) &= \frac{\alpha_s}{2\pi^2}\frac{1}{\vec{k}_\perp^2}C_F\int\frac{dx}{x}f_1(x)\left[\frac{1+\xi^2}{(1-\xi)_+}+\delta(1-\xi)\left(\ln\frac{x_B^2\zeta^2}{\vec{k}_\perp^2}-1\right)\right],\\
g_{1L}(x_B, k_\perp) &= \frac{\alpha_s}{2\pi^2}\frac{1}{\vec{k}_\perp^2}C_F\int\frac{dx}{x}g_{1L}(x)\left[\frac{1+\xi^2}{(1-\xi)_+}+\delta(1-\xi)\left(\ln\frac{x_B^2\zeta^2}{\vec{k}_\perp^2}-1\right)\right],\\
h_1(x_B, k_\perp) &= \frac{\alpha_s}{2\pi^2}\frac{1}{\vec{k}_\perp^2}C_F\int\frac{dx}{x}f_1(x)\left[\frac{2\xi}{(1-\xi)_+}+\delta(1-\xi)\left(\ln\frac{x_B^2\zeta^2}{\vec{k}_\perp^2}-1\right)\right],
\end{aligned}
$$

where the color factor $C_F = (N_c^2-1)/2N_c$ with $N_c = 3$, $\xi = x_B/x$ and $\zeta^2 = (2v\cdot P)^2/v^2$.

TMDs: QCD based predictions

Large-x limit



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

Brodsky & Yuan (2006)

Burkardt (2007)

$f_{1T}^\perp \sim (1-x)^4$ $\quad g_{1T}^\perp \sim (1-x)^4$ $\quad h_1 \sim (1-x)^3$ $\quad h_{1T}^\perp \sim (1-x)^5$

Large-Nc limit (Pobilitsa)

$f_1^{\perp u} > 0, f_1^{\perp d} > 0$ $\quad h_1^{\perp u} < 0, h_1^{\perp d} < 0$

Do not change sign (isoscalar)

$f_{1T}^{\perp u} < 0, f_{1T}^{\perp d} > 0$

All others change sign
u→d (isovector)

The Multi-Hall SIDIS Program at 12 GeV

H. Avakian, F. Benmokhtar, J-P. Chen, R. Ent, K. Griffioen, K. Hafidi, J. Huang, K. Joo, N. Kalantarians, M. Mirazita, H. Mkrtchyan, A. Prokudin, X. Qian, Y. Qiang, B. Wojtsekhowski

for the Jlab SIDIS working group

•Inclusive and semi-inclusive deep inelastic scattering (DIS and SIDIS) are important tools for understanding the structure of nucleons and nuclei.

•Spin asymmetries in polarized SIDIS are directly related to transverse momentum dependent parton distributions (TMDs) and fragmentation functions, and are the subject of intense theoretical and experimental study.

•The TMDs, which depend also on the intrinsic transverse momentum of the parton, $\mathbf{k}_T$, provide a three-dimensional partonic picture of the nucleon in momentum space.

•Measurements with pions and kaons in the final state will provide important information on the hadronization mechanism in general and on the role of spin-orbit correlations in the fragmentation in particular.