SIDIS measurements of transverse and longitudinal spin azimuthal asymmetries related to higher twist PDFs

Harut Avakian (JLab)

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TRANSVERSITY 2011 - Third International Workshop on Transverse Polarization Phenomena in Hard Scattering

from Monday 29 August 2011 at **08:00** to Friday 02 September 2011 at **20:35** (Europe/Zagreb)
at Veli Lošinj (Croatia)

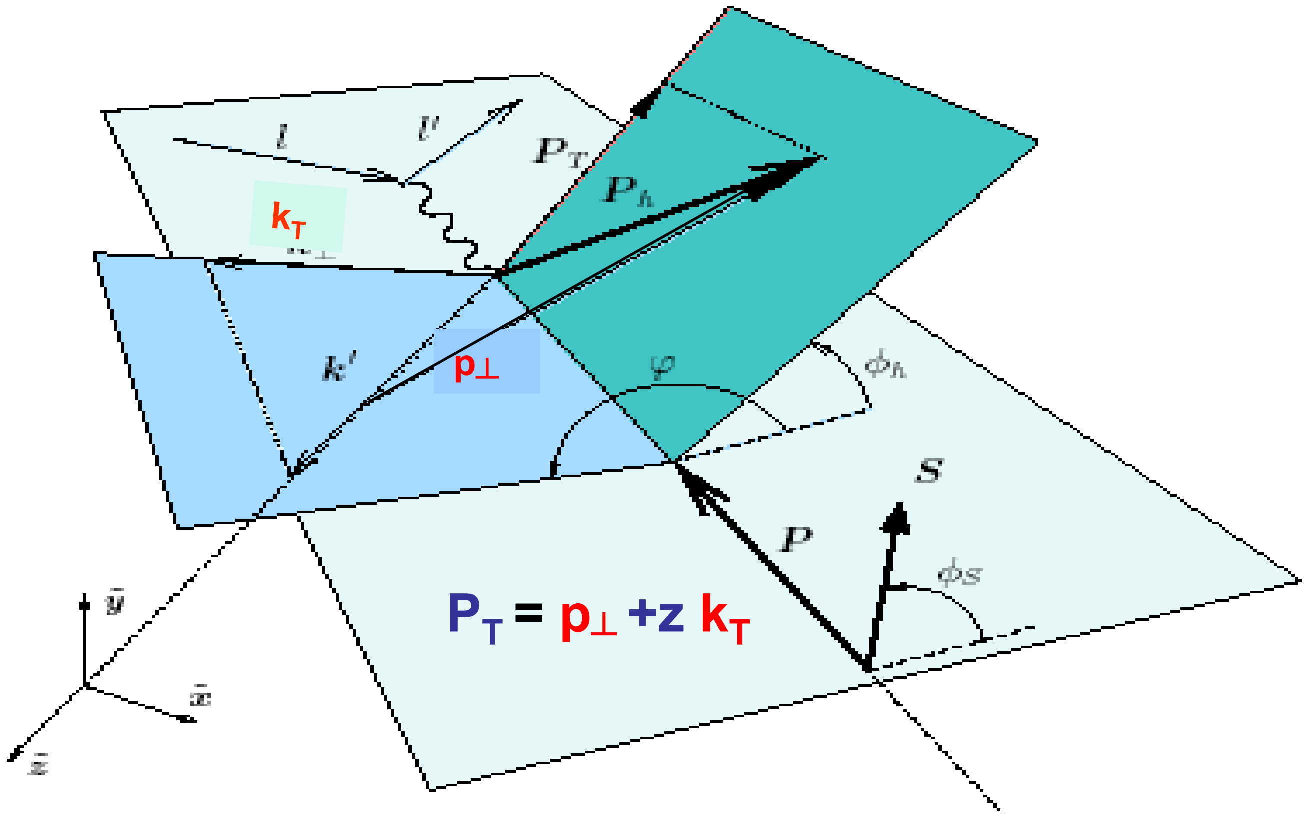
Outline

- Higher twists in SIDIS
  - quark-gluon correlations
  - experimental results
  - model calculations and lattice simulations
- Future measurements
  - measuring higher twist distributions in di-hadron production
  - extraction of HT functions from azimuthal asymmetries
- Physics background to leading observables
- Summary

Quark-gluon correlations (like k_T-effects) lead to azimuthal modulations in hadron production in hard scattering processes.

SIDIS kinematical plane

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



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

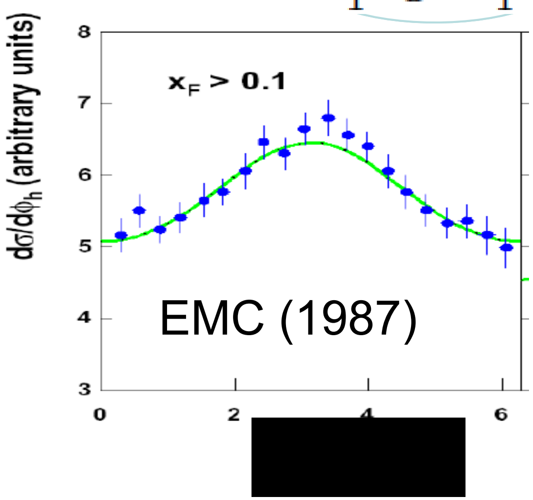
Azimuthal distributions in SIDIS

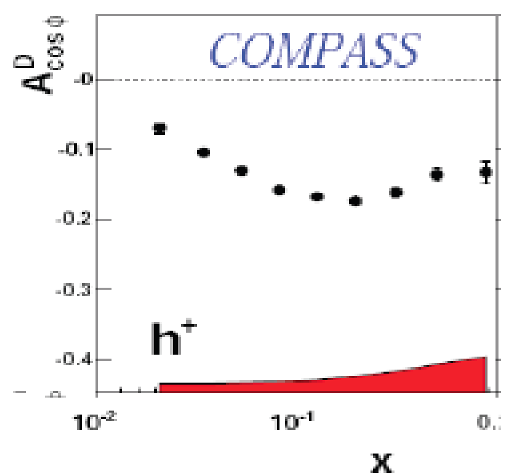
$f_1 \otimes D_1$ h.t. h.t.

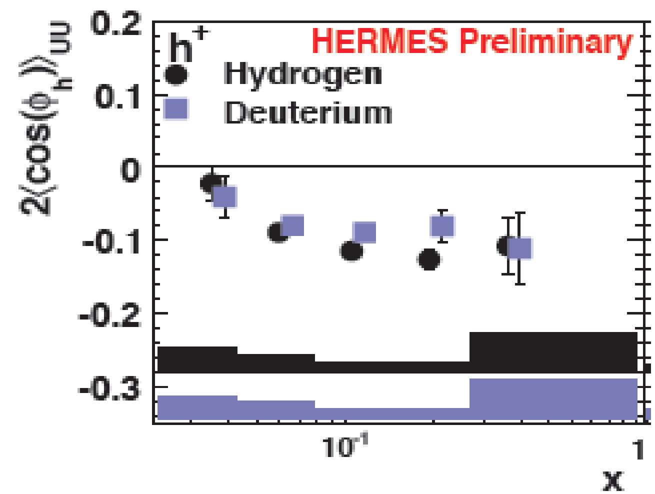
$$\frac{d\sigma}{dx_B\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2}\,\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

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

$h_1^\perp \otimes H_1^\perp$ h.t.







Large cosϕ modulations observed by EMC were reproduced in electroproduction of hadrons in SIDIS with unpolarized targets at COMPASS and HERMES

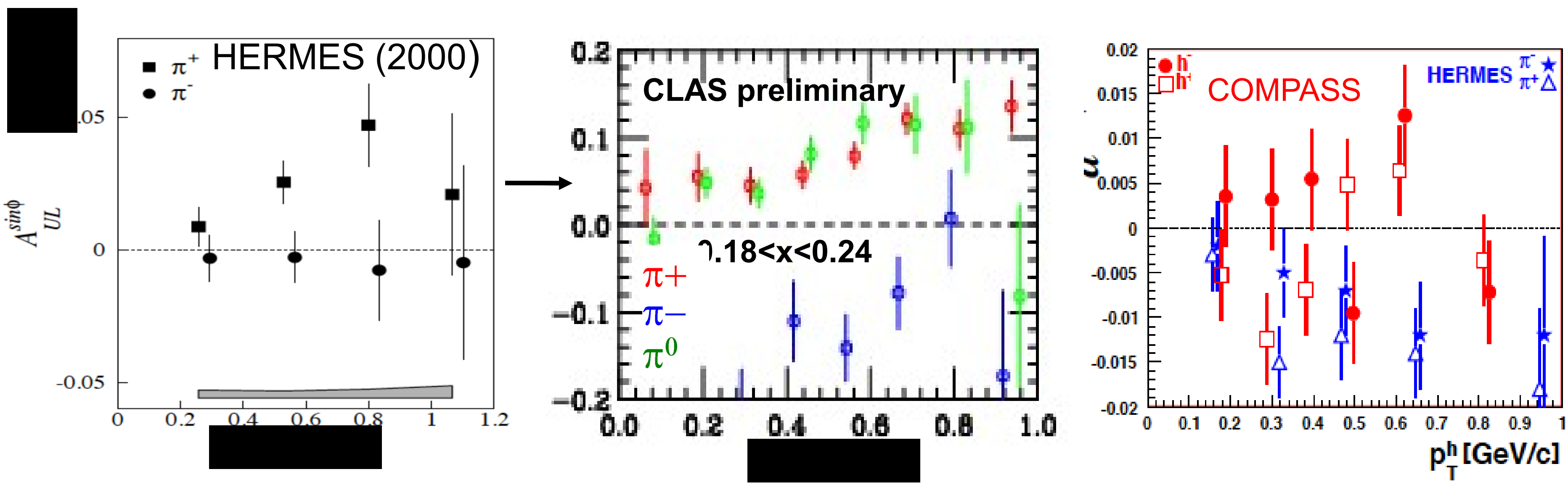
Measurements of SS azimuthal asymmetries in SIDIS

h.t. $\qquad h_{1L}^{\perp} \otimes H_1^{\perp}$

$$\frac{d\sigma}{dx\,dy\,d\phi_S\,d\phi_h\,dP_{h\perp}^2} \propto S_L\left[\sqrt{2\epsilon(1+\epsilon)}\,sin\phi_h F_{UL}^{sin\phi_h} + \epsilon\, sin(2\phi_h) F_{UL}^{sin(2\phi_h)}\right]$$

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

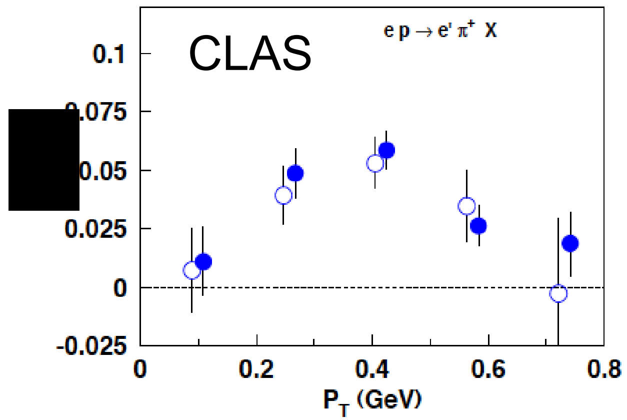
$g_{1L} \otimes D_1 \qquad$ h.t.

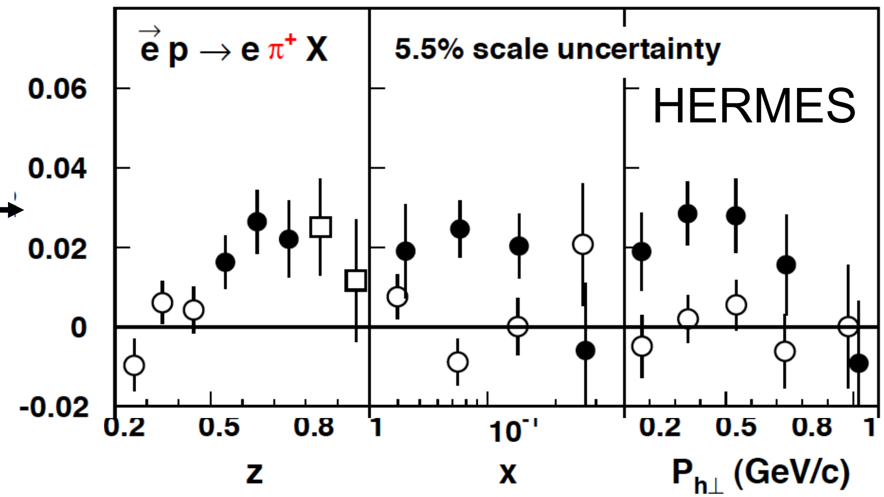


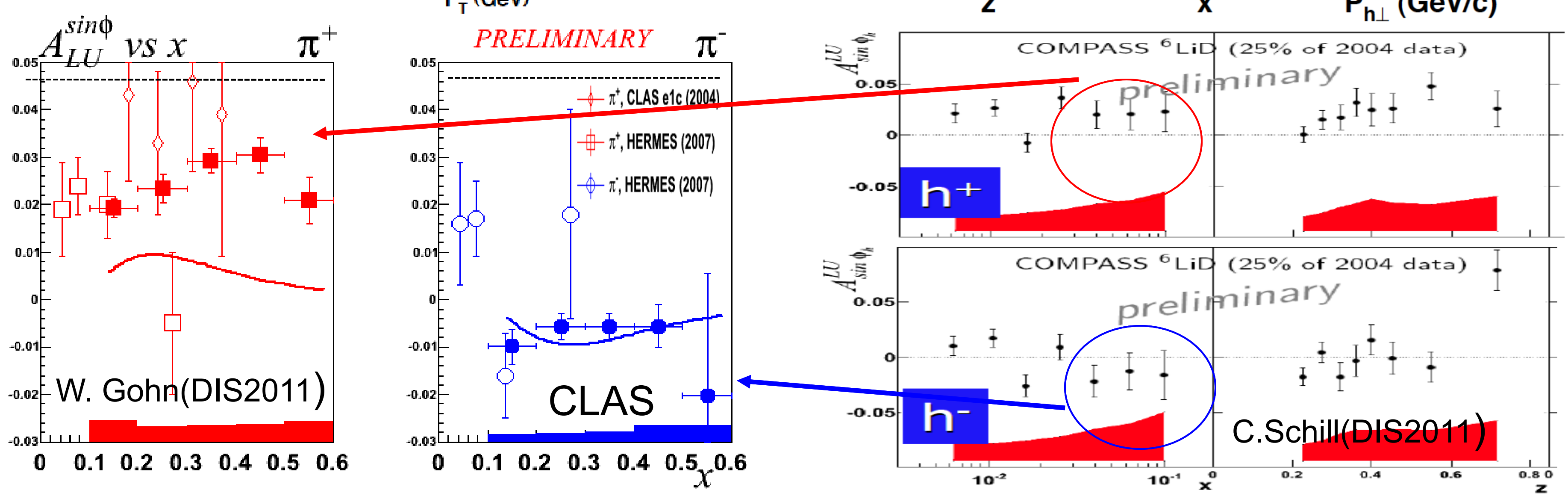
Large sinϕ modulations have been observed in electroproduction of hadrons in SIDIS with longitudinally polarized targets

Beam SSA: A_{LU} Jlab/HERMES/COMPASS

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

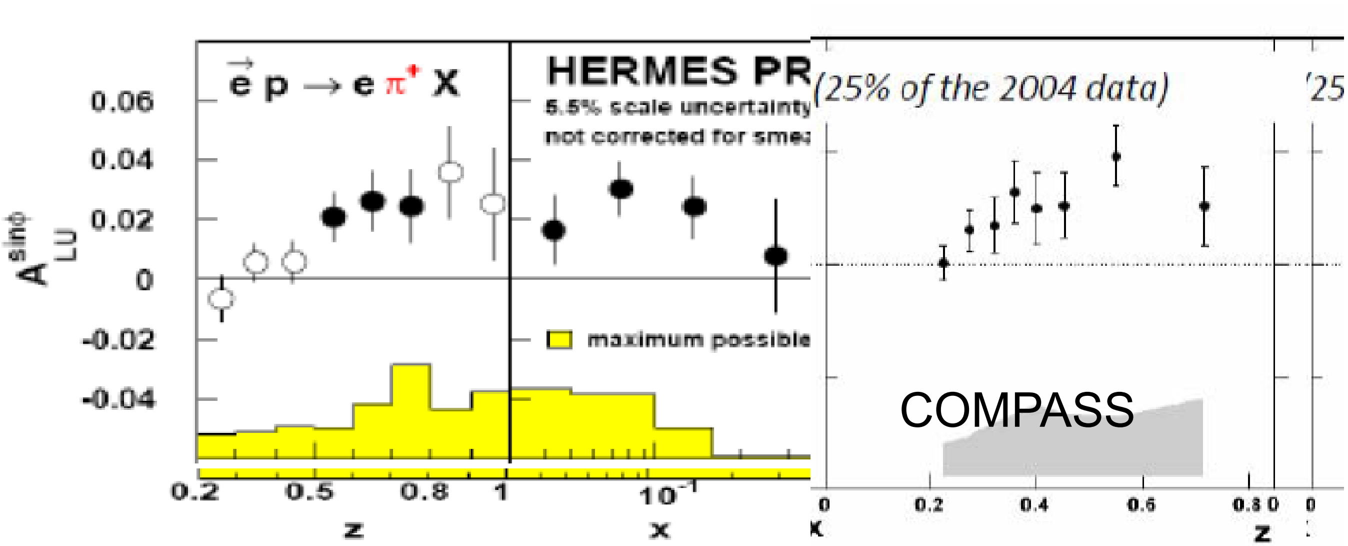


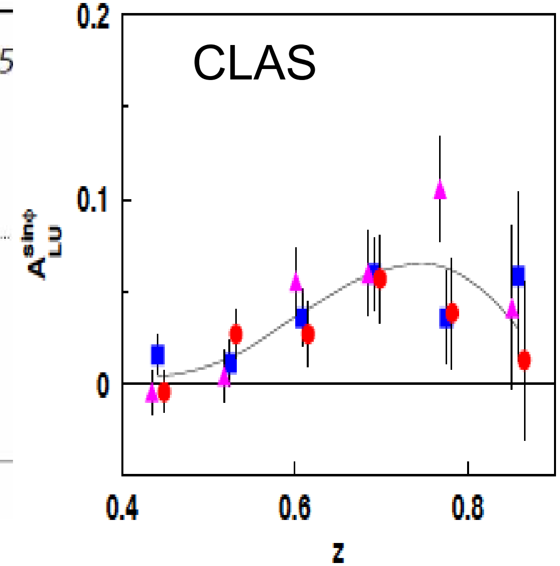




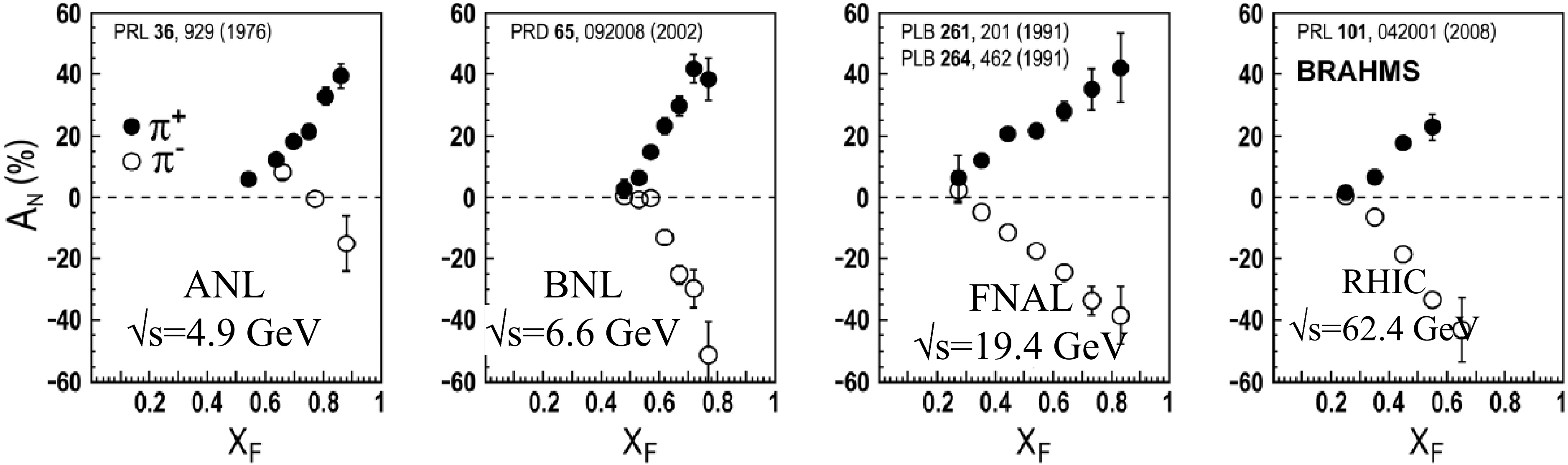
HT SSAs are comparable at JLab, HERMES and COMPASS

SSA at large x_F



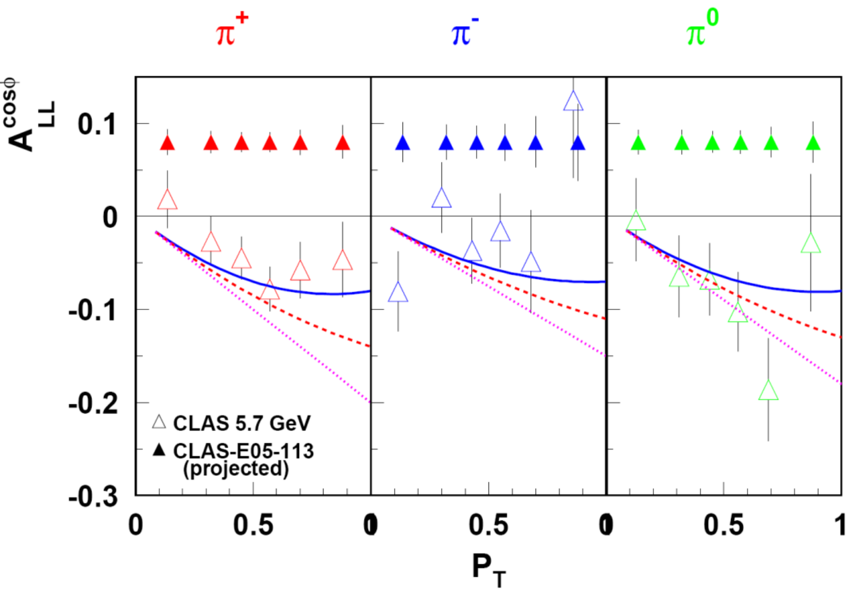


0 moves to lower x_F with energy?



More polarized target HT SSAs

Longitudinally polarized

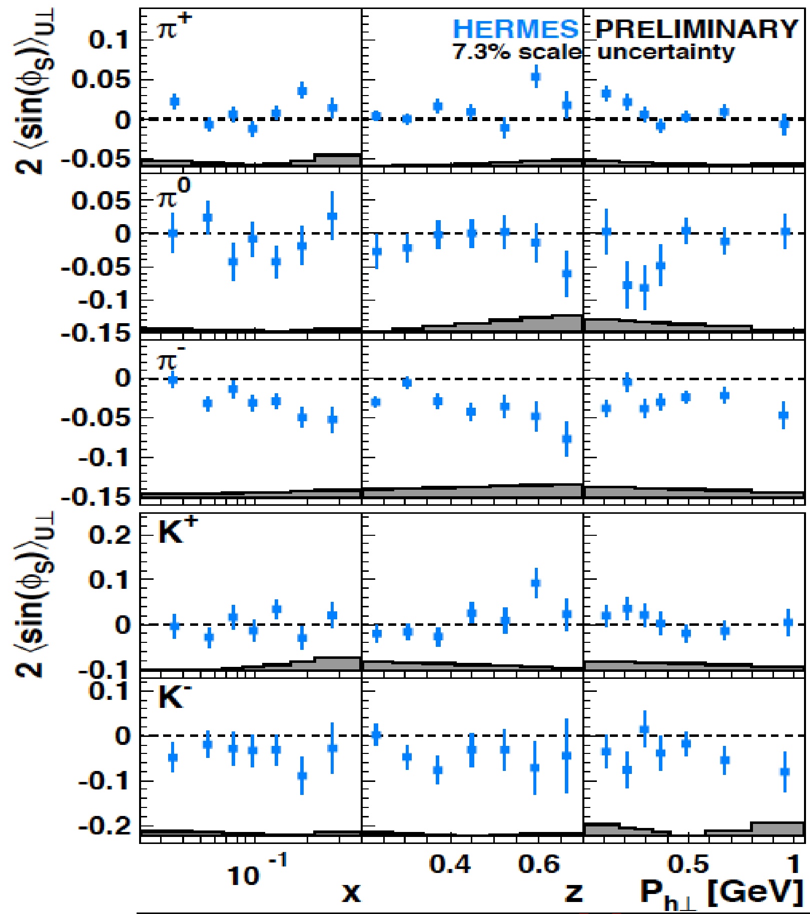


$$A_{LL}^{\cos\phi} \sim e_L H_1^{\perp}$$

$$A_{LL}^{\cos\phi} \sim g_L^{\perp} D_1$$

How transversely polarized quarks were generated?

Transversely polarized



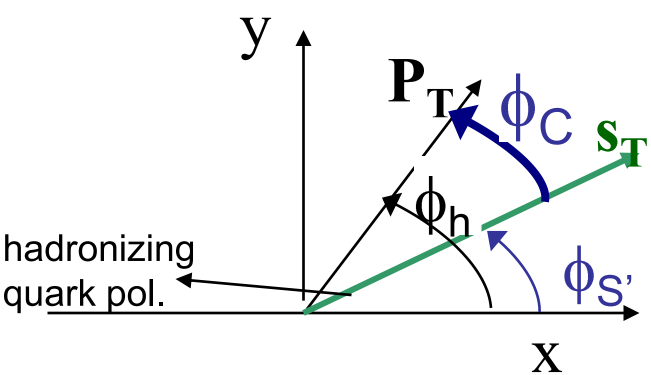
$$f_T D_1 - \frac{M_h}{M} x h_T H_1^{\perp}$$

Sivers type

Collins type

Collins Effect: azimuthal modulation of the fragmentation function

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



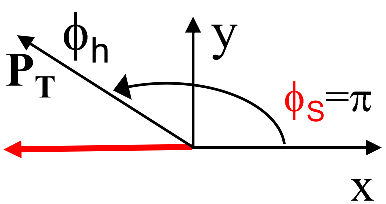
N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 , $h_{1T}^{\perp}$

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

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

Contributions in large sinusoidal modulations observed in experiments from Collins fragmentation

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



$$\begin{matrix} eH_1^{\perp} \\ h_L H_1^{\perp} \end{matrix} \quad \sin\phi_h$$

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

What makes them transversely polarized in the lepton plane?

Transverse force on the polarized quarks

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

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

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

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

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)

More sum rules

$$\int_0^1 dx\, (e^u + e^{\bar{u}} + e^d + e^{\bar{d}})(x) = \frac{\sigma_{\pi N}}{m}$$

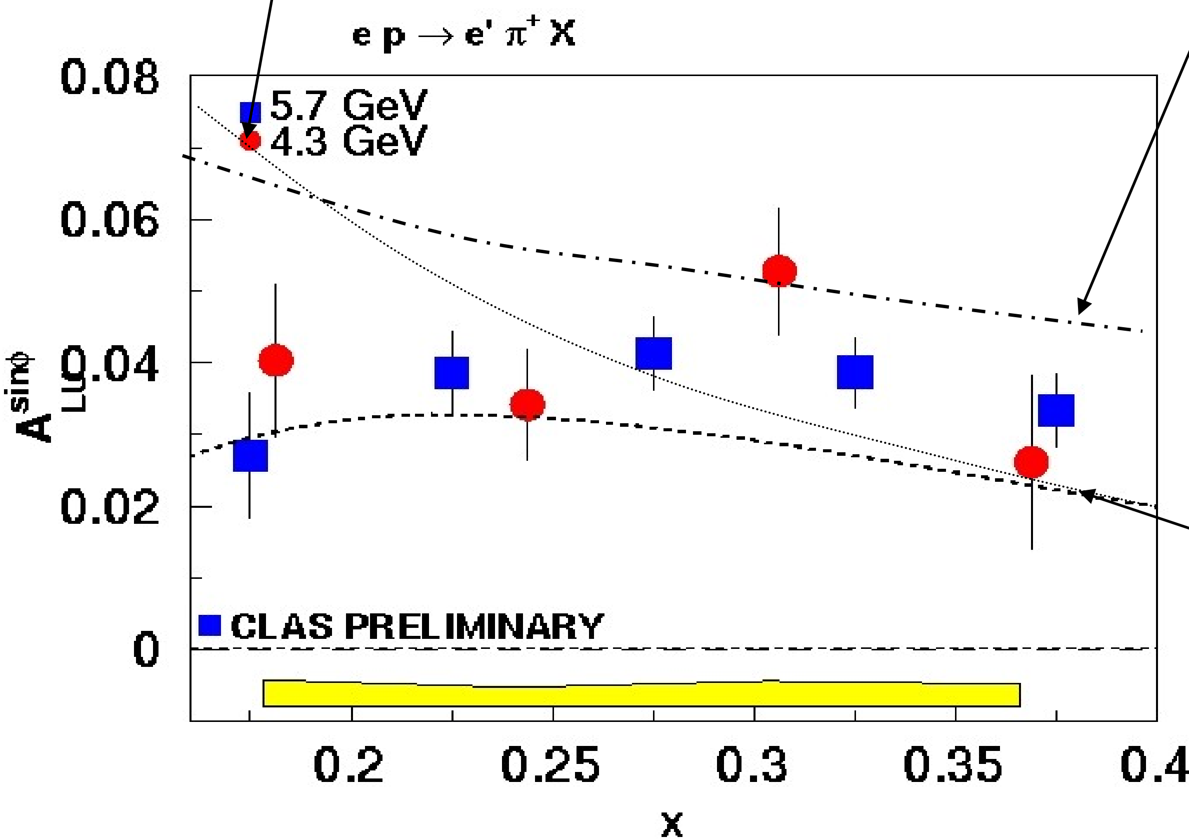
$$\int_0^1 dx\, x(e^q - e^{\bar{q}})(x) = \frac{m_q}{M_N}$$

current quark masses

Beam SSA: A_{LU} from CLAS @ JLab

$$g^{\perp} D_1(z)$$

Photon Sivers Effect Afanasev & Carlson, Metz & Schlegel, Gamberg et al.



$$h_1^{\perp}(x) E(z)$$

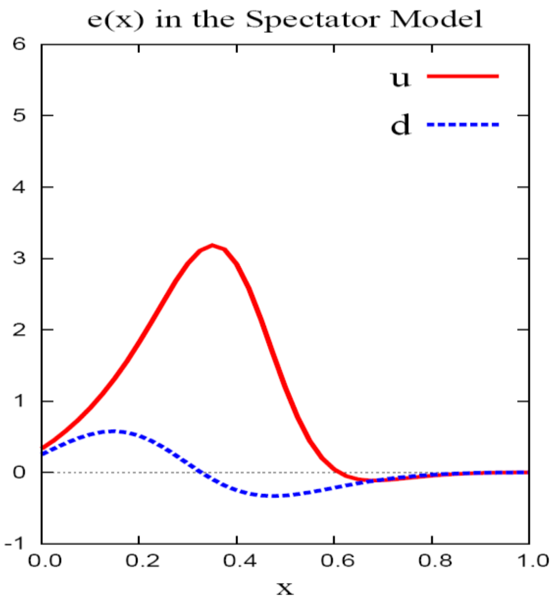
Beam SSA from initial distribution (Boer-Mulders TMD) F.Yuan using $h_1^{\perp}$ from MIT bag model

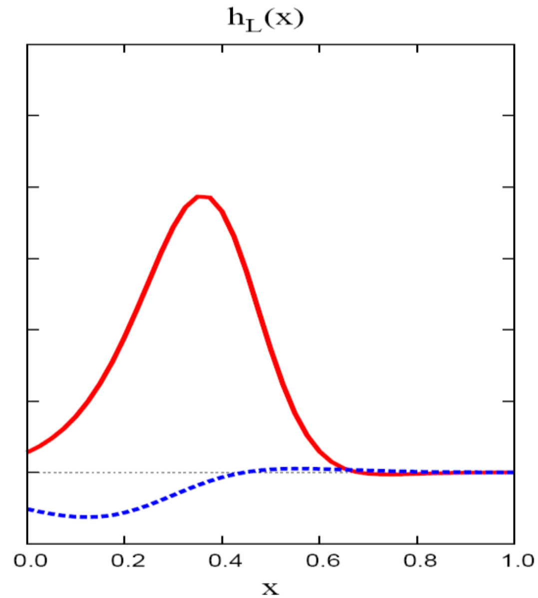
Beam SSA from hadronization (Collins effect) by Schweitzer et al.

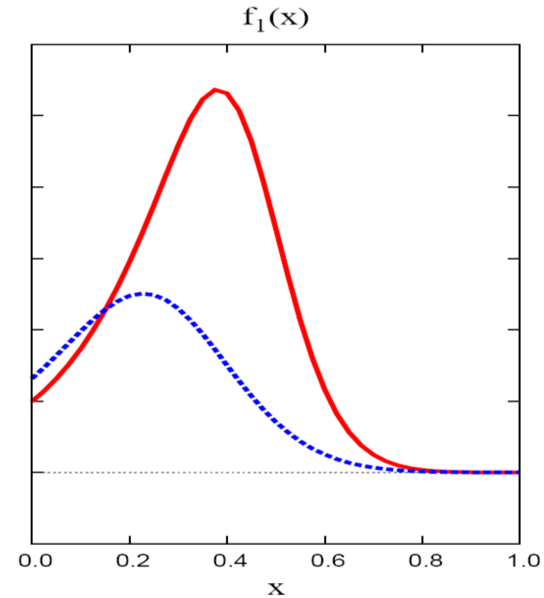
$$e(x) H_1^{\perp}(z)$$

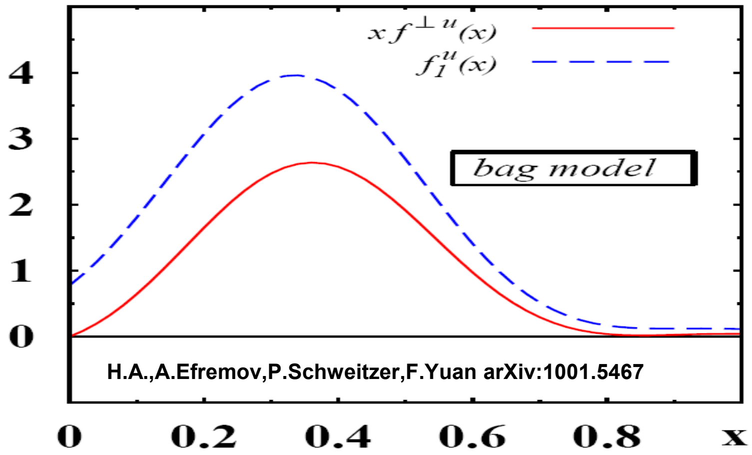
N/q	U	L	T
U			e
L			h_L
T		g_T	

Model predictions for higher twists









$$F_{UU}^{\cos\phi} \propto f^{\perp q} D_1^q$$

$$x f^{\perp q} = x\tilde{f}^{\perp q} + f_1^q$$

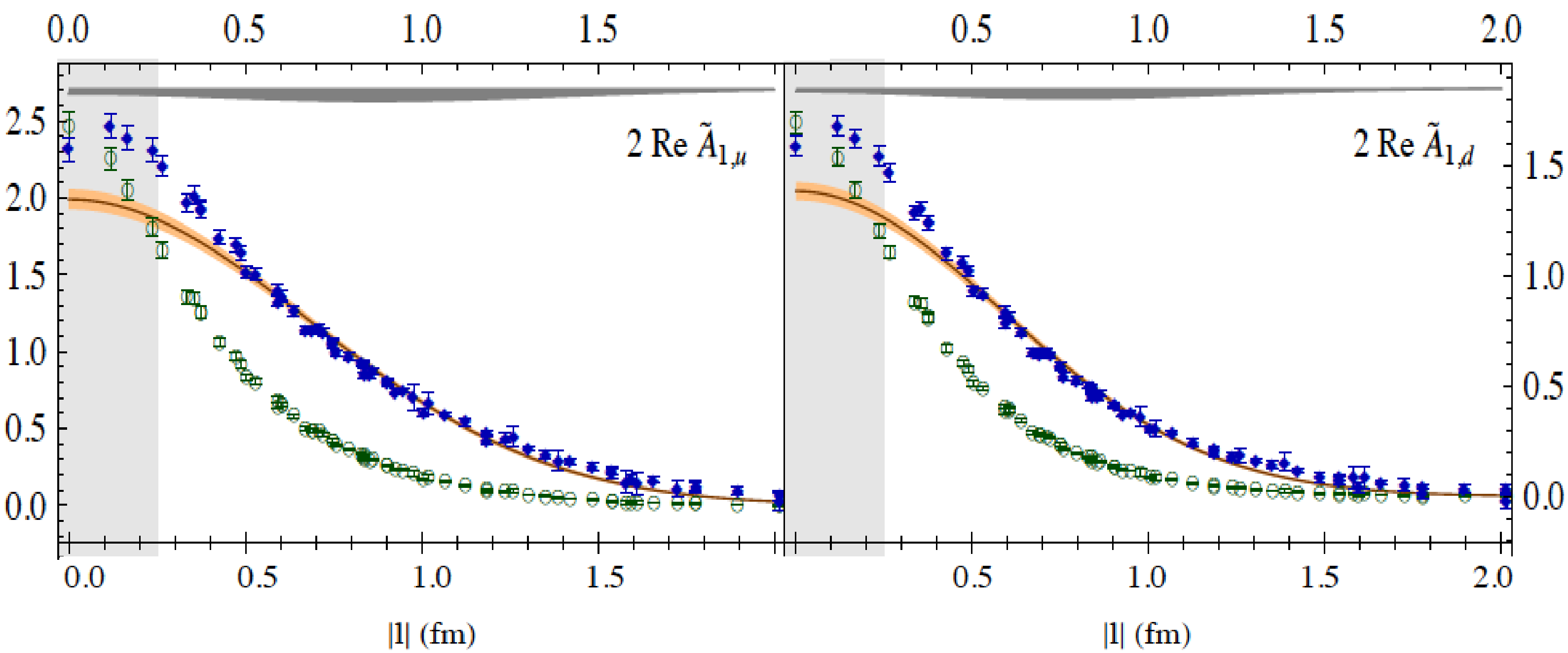
"interaction dependent"

Models agree on a large HT distributions

Lattice calculations of HT distributions

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

(PDFs in terms of Lorenz invariant amplitudes
Musch et al, arXiv:1011.1213)

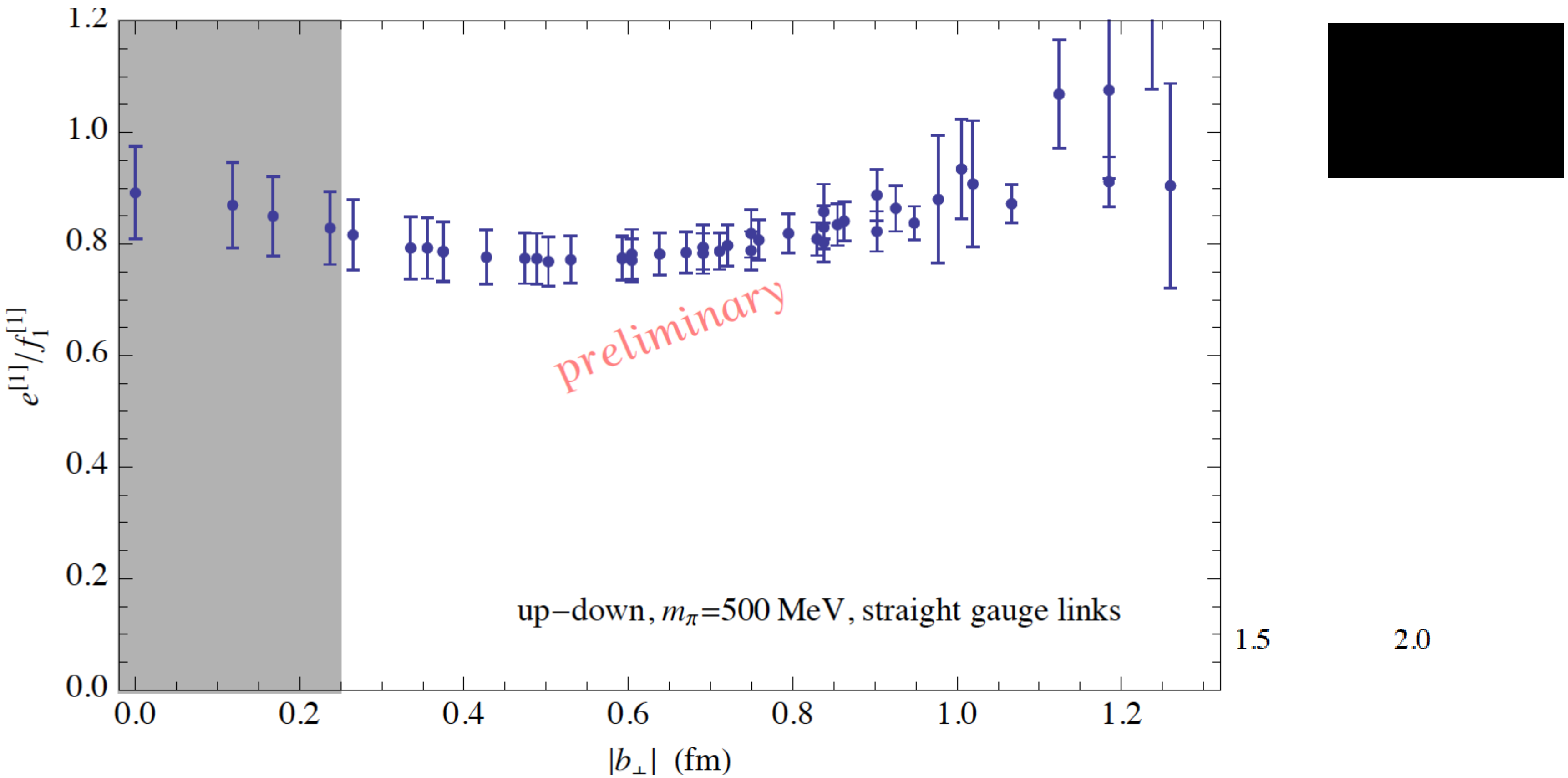


Lattice provides important complementary information on FT for all HT distributions

Lattice calculations of HT distributions

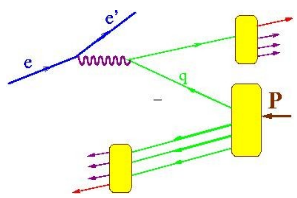
Lattice provides important cross check with data and models for all HT TMDs (Musch et al, arXiv:1011.1213)

$$f_1^{[1]}(\boldsymbol{k}_\perp^2) \equiv \int_{-1}^{1} dx\ f_1(x, \boldsymbol{k}_\perp^2)$$

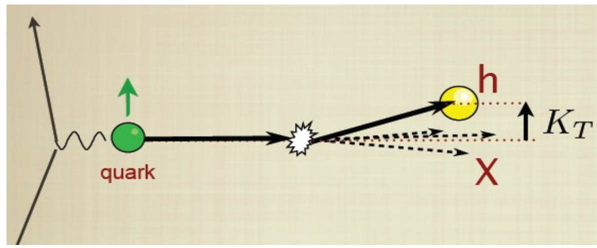


Lattice results for u-d can be directly compared to models and data.

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



h



Twist-2

N/q	U	L	T
U	$\mathbf{f_1}$		$h_1^\perp$

Twist-3

N/q	U	L	T
U	$f^\perp$	$g^\perp$	h, $\mathbf{e}$

A. Bacchetta *et al.* hep-ph/0611265

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{h}\cdot k_T}{M_h}\left(xe\,H_1^\perp + \frac{M_h}{M}\,f_1\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{h}\cdot p_T}{M}\left(xg^\perp D_1 + \frac{M_h}{M}\,h_1^\perp\frac{\tilde{E}}{z}\right)\right]$$

•Several unknown distribution and fragmentation functions involved, making extraction model dependent

•Factorization of higher twists in k_T-dependent SIDIS not proved

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

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

$$\Downarrow$$

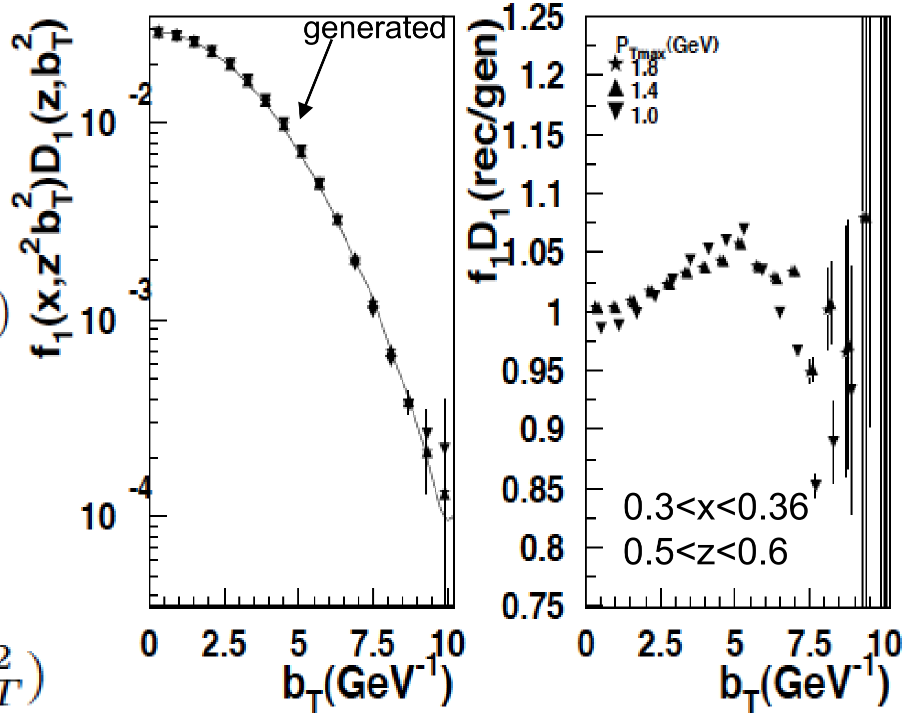
$$S_\pi^{unp\pm}(x_i,z_i,b_{Tj}) = \sum_{i=1}^{N_\pi^+/N_\pi^-} J_0(b_{Tj}P_{Ti})/\eta_i/A(x_i,y_i)$$

acceptance

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

$$\Downarrow$$

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



Bessel weighting

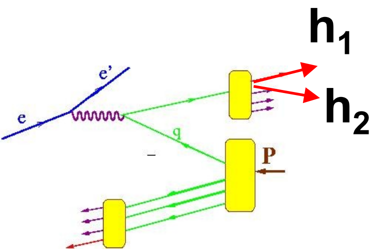
$$\int_0^{2\pi} d\phi_h \sin\phi_h \int_0^\infty d|\mathbf{P_{h\perp}}||\mathbf{P_{h\perp}}|\frac{2J_1(|\mathbf{P_{h\perp}}||\mathbf{b_T}|)}{zM_h|\mathbf{b_T}|}\left[\frac{d\sigma}{dxdydzd\phi_h|\mathbf{P_{h\perp}}|d|\mathbf{P_{h\perp}}|}\right]$$

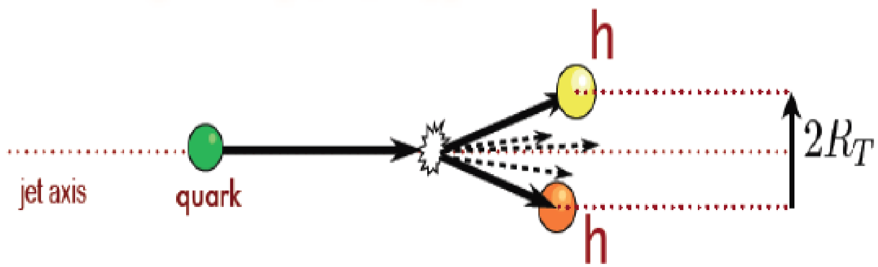
[redacted]

- provides a model independent way to study kinematical dependences of TMD requires wide range in hadron P_T

Dihadron Fragmentation

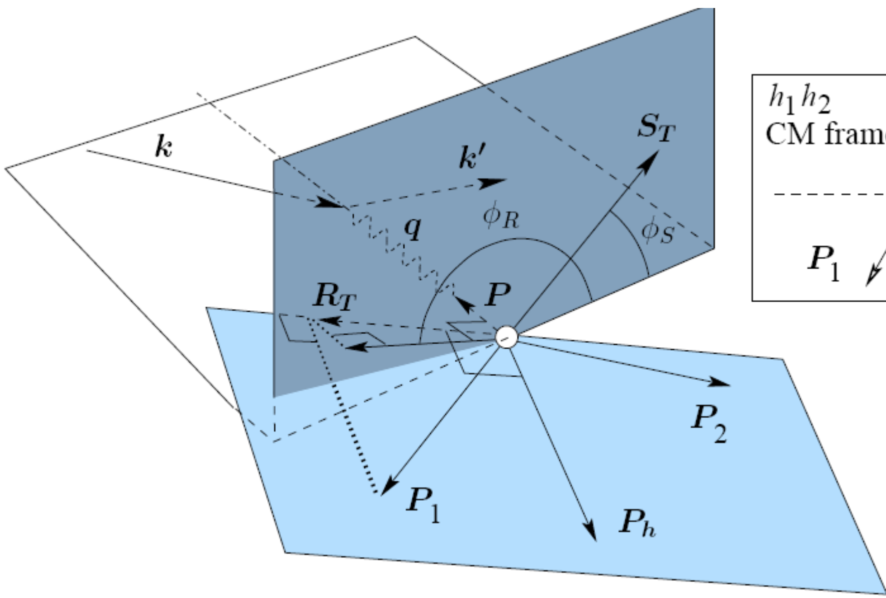
[redacted] - fractions of energy carried by a hadrons

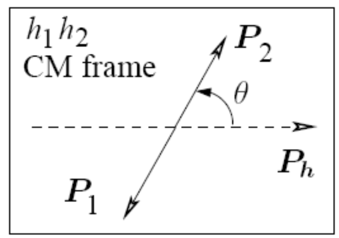




DiFF

[redacted]





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

$$\phi_R \equiv \frac{(\boldsymbol{q}\times\boldsymbol{k})\cdot\boldsymbol{R_T}}{|(\boldsymbol{q}\times\boldsymbol{k})\cdot\boldsymbol{R_T}|}$$

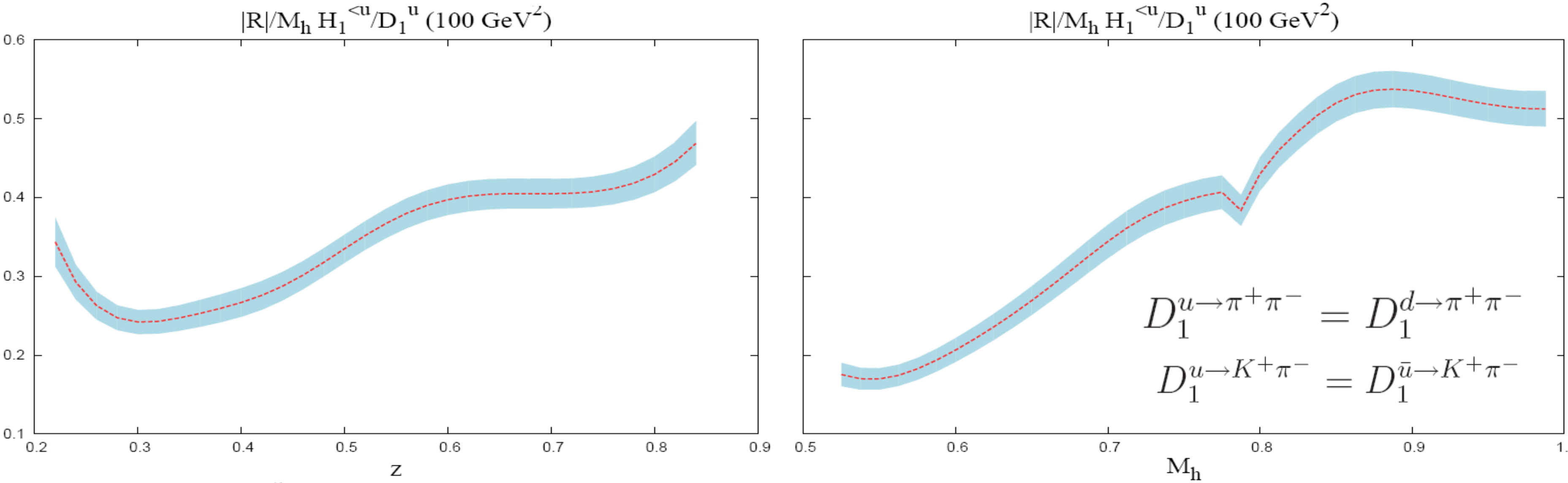
$$\boldsymbol{R_T} = \boldsymbol{R} - (\boldsymbol{R}\cdot\hat{\boldsymbol{P}}_h)\hat{\boldsymbol{P}}_h$$

$$\boldsymbol{R} \equiv (\boldsymbol{P_1} - \boldsymbol{P_2})/2$$

Dihadron productions offers exciting possibility to access HT effects

Dihadron Fragmentation

BELLE Collaboration, A. Vossen et al., Phys.Rev.Lett. (2011), 1104.2425.



The ratio $|\boldsymbol{R}|H_{1,sp}^{\sphericalangle,u}(z,M_h)/M_h D_1^u(z,M_h)$ at the Belle's scale

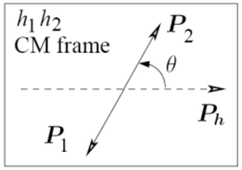
•Significant DiFF published by BELLE

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

- 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

Dihadron Fragmentation

Dihadron production cross section in case of one photon exchange



$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_R\,dM_h^2\,d\cos\theta} = \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \varepsilon\,F_{UU,L}$$

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

$$+ S_L\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_R\,F_{UL}^{\sin\phi_R} + \varepsilon\sin(2\phi_R)\,F_{UL}^{\sin 2\phi_R}\right] + S_L\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_R\,F_{LL}^{\cos\phi_R}\right] + \ldots\Big\}$$

$$F_{LU}^{\sin\phi_R} = -x_B\frac{|\boldsymbol{R}|\sin\theta}{Q}\left[\frac{M}{M_h}\,x_B\,e^q(x_B)\,H_1^{\sphericalangle q}(z,\cos\theta,M_h) + \frac{1}{z}\,f_1^q(x_B)\,\widetilde{G}^{\sphericalangle q}(z,\cos\theta,M_h)\right]$$

$$F_{UL}^{\sin\phi_R} = -x_B\frac{|\boldsymbol{R}|\sin\theta}{Q}\left[\frac{M}{M_h}\,x_B\,h_L^q(x_B)\,H_1^{\sphericalangle q}(z,\cos\theta,M_h) + \frac{1}{z}\,g_1^q(x_B)\,\widetilde{G}^{\sphericalangle q}(z,\cos\theta,M_h)\right]$$

Higher twist sinϕ asymmetries have much simpler structure than for single hadron case

HT in fragmentation

SSA in Dihadron production

$$A_{LU}^{\sin\phi_R \sin\theta}(x,y,z,M_h,Q) \sim \frac{H_{1,sp}^{\sphericalangle,u}\left[4xe^{u-\bar{u}}(x) - xe^{d-\bar{d}}(x)\right] + \frac{M_h}{zM}\cancel{\tilde{G}_{sp}^{\sphericalangle,u}}\left[4xf_1^{u-\bar{u}}(x) - xf_1^{d-\bar{d}}(x)\right]}{D_1^u\left[4f_1^{u+\bar{u}}(x) + f_1^{d+\bar{d}}(x)\right] + D_1^s\, f_1^{s+\bar{s}}(x)}$$

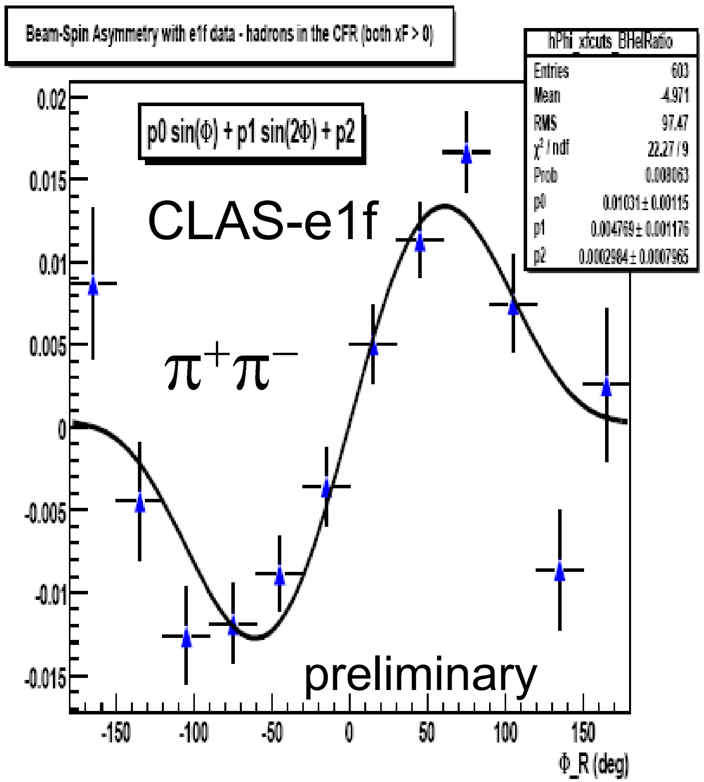
$$A_{UL}^{\sin\phi_R \sin\theta}(x,y,z,M_h,Q) \sim \frac{H_{1,sp}^{\sphericalangle,u}\left[4xh_L^{u-\bar{u}}(x) - xh_L^{d-\bar{d}}(x)\right] + \frac{M_h}{zM}\cancel{\tilde{G}_{sp}^{\sphericalangle,u}}\left[4xg_1^{u-\bar{u}}(x) - xg_1^{d-\bar{d}}(x)\right]}{D_1^u\left[4f_1^{u+\bar{u}}(x) + f_1^{d+\bar{d}}(x)\right] + D_1^s\, f_1^{s+\bar{s}}(x)}$$

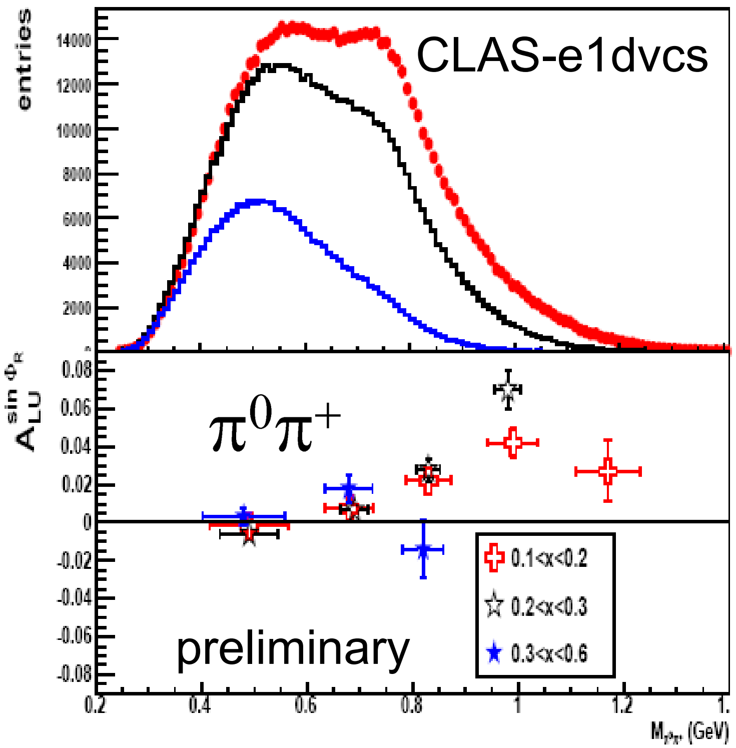
$$\downarrow$$

$$A_{UL}^{\sin\phi_R \sin\theta}\frac{1}{4g_1^{u-\bar{u}}(x) - g_1^{d-\bar{d}}(x)} - A_{LU}^{\sin\phi_R \sin\theta}\frac{1}{4f_1^{u-\bar{u}}(x) - f_1^{d-\bar{d}}(x)}$$

Difference of asymmetries measured with unpolarized and longitudinally polarized targets depends only on the DiFF and HT functions

Dihadron beam SSA with CLAS6



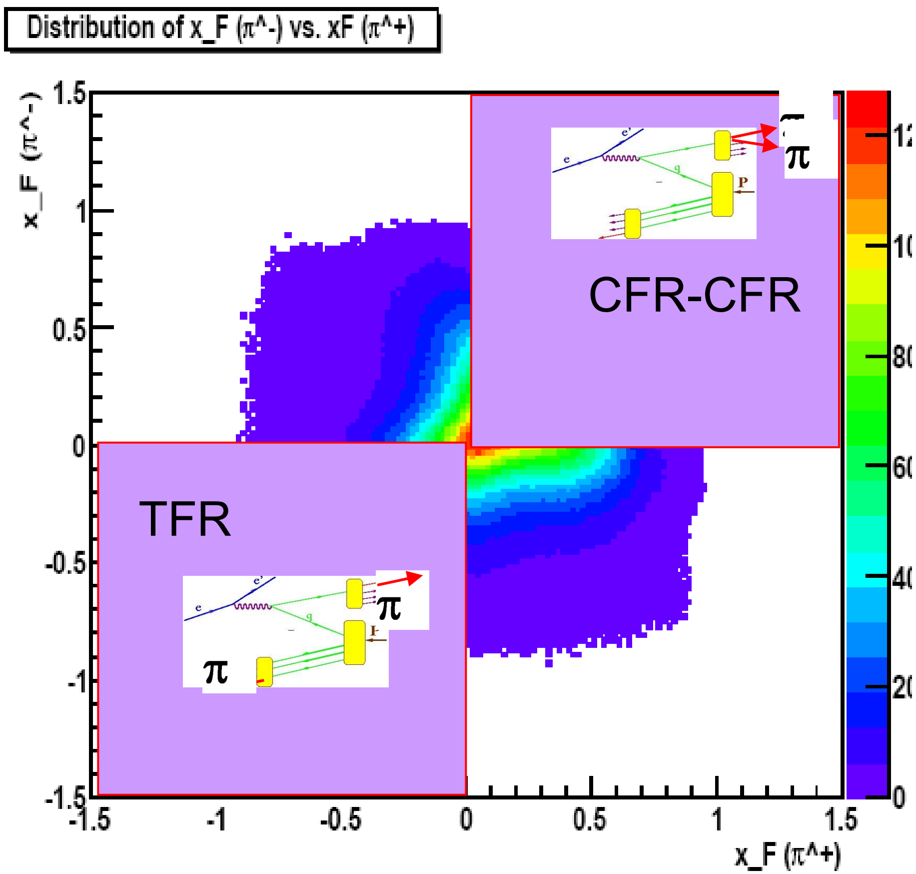


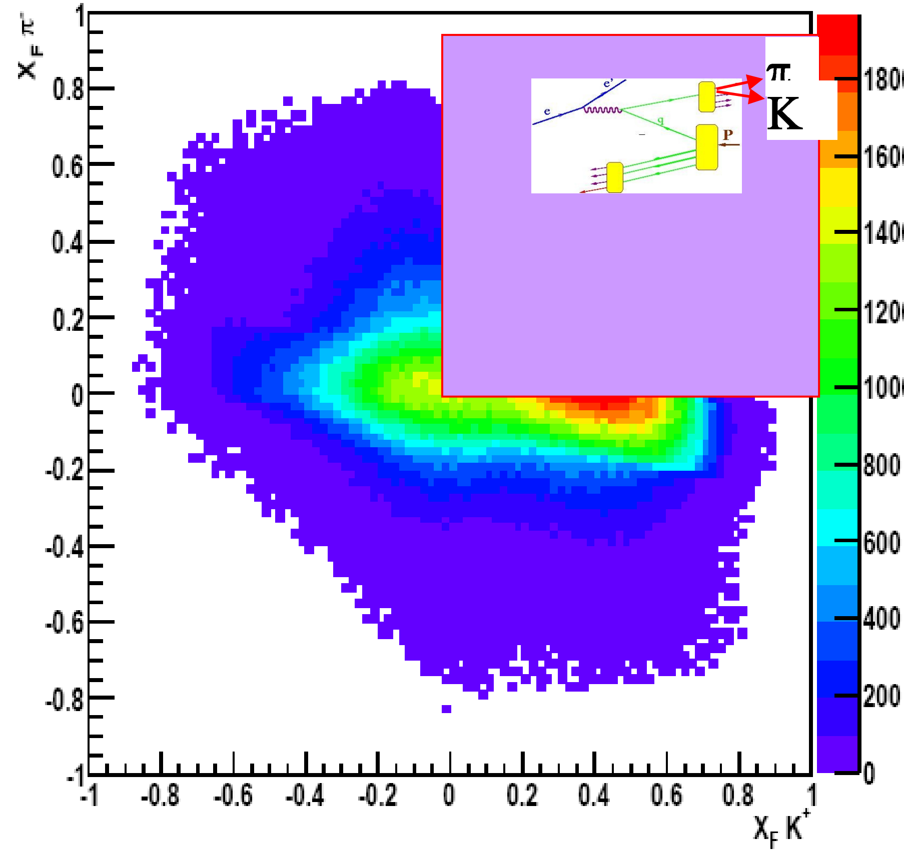
Significant dihadron asymmetries measured at 6 GeV by CLAS

Dihadron production with CLAS12

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

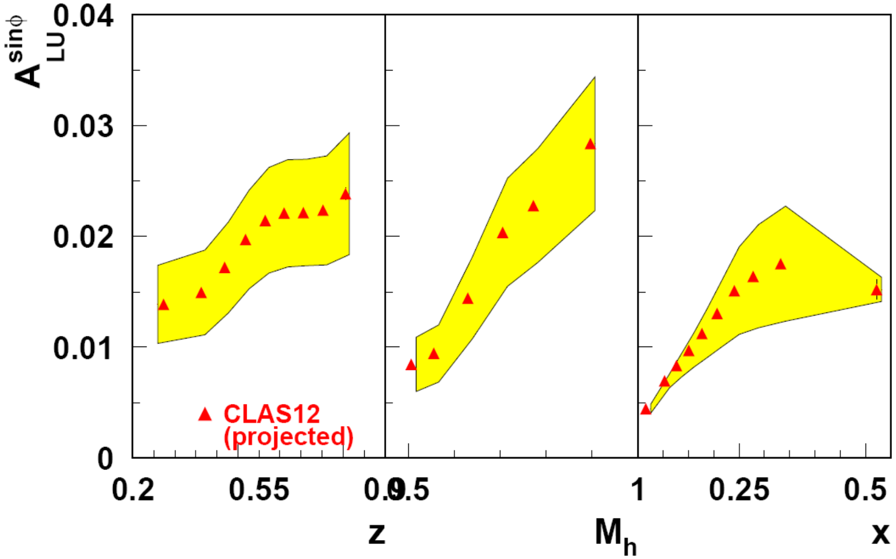
x_F - momentum in the CM frame





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

Dihadron production with CLAS12



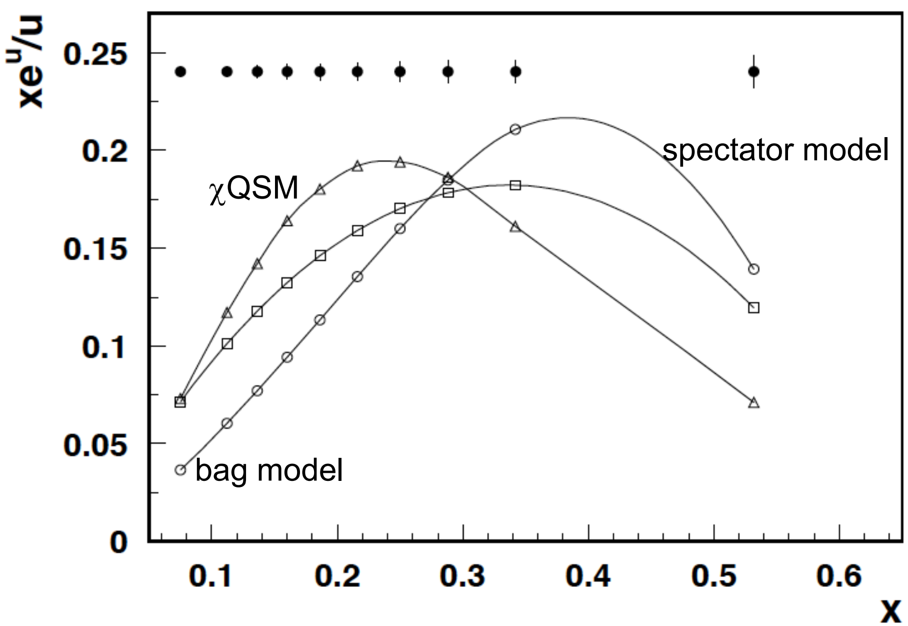
Assuming SU(6) symmetry

$$\frac{7}{9}\frac{xe^u(x)}{f_1^u(x)} = -\frac{A(y)}{W(y)}\left(\frac{M}{Q}\,\frac{1}{2}\,\frac{|\mathbf{R}|}{M_h}\right)^{-1}\frac{D_1^q(z,M_h)}{H_1^{\sphericalangle,q}(z,M_h)}A_{LU}^{\sin\phi_R\sin\theta}$$

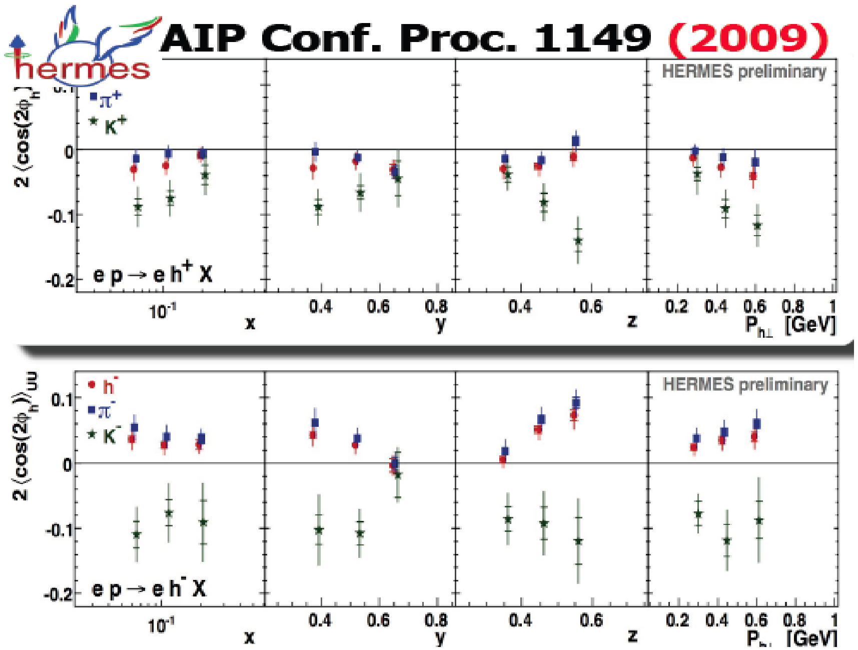
u-dominance

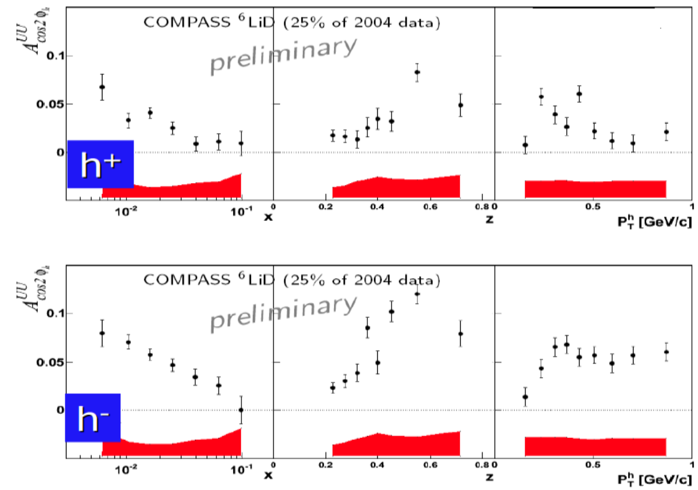
$$\frac{xe^u(x)}{f_1^u(x)} = -\frac{A(y)}{W(y)}\left(\frac{M}{Q}\,\frac{1}{2}\,\frac{|\mathbf{R}|}{M_h}\right)^{-1}\frac{D_1^q(z,M_h)}{H_1^{\sphericalangle,q}(z,M_h)}A_{LU}^{\sin\phi_R\sin\theta}$$

JLab PR12-11-109: 54 days of unpolarized proton and deuteron running will allow precision measurement of HT distribution e



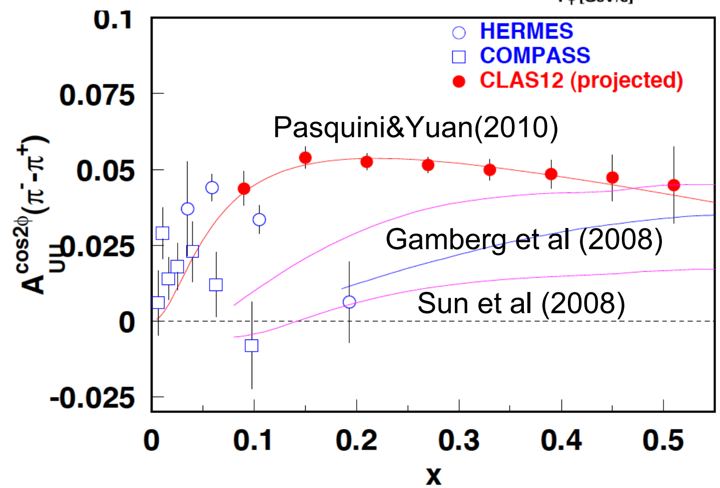
HT effects as background: Boer-Mulders distribution





Background contributions :
Higher twist azimuthal moments
kinematical HT (Cahn)
dynamical HT (Berger-Brodsky)
Radiative correction
Acceptance

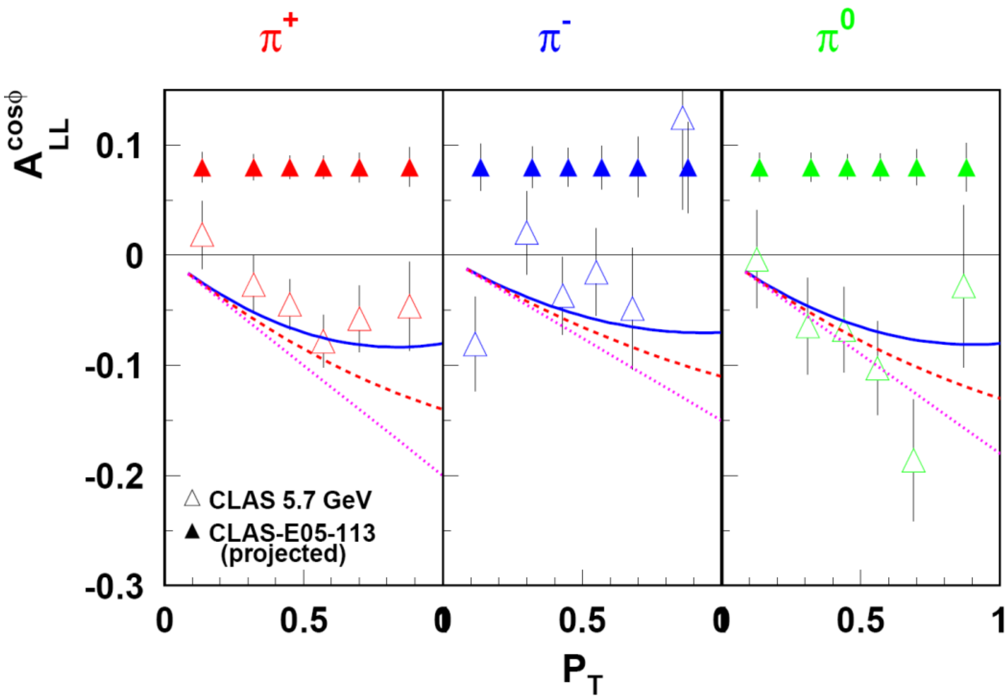
"flavor blind"



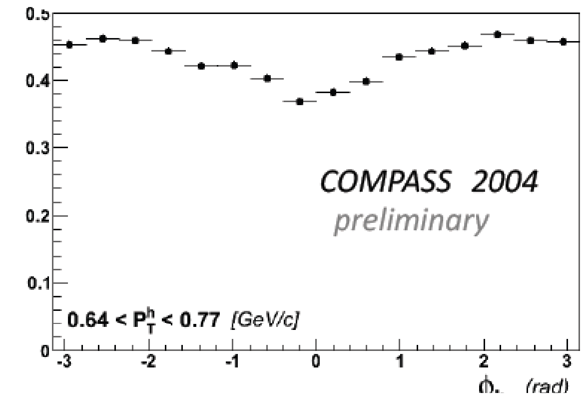
[redacted]

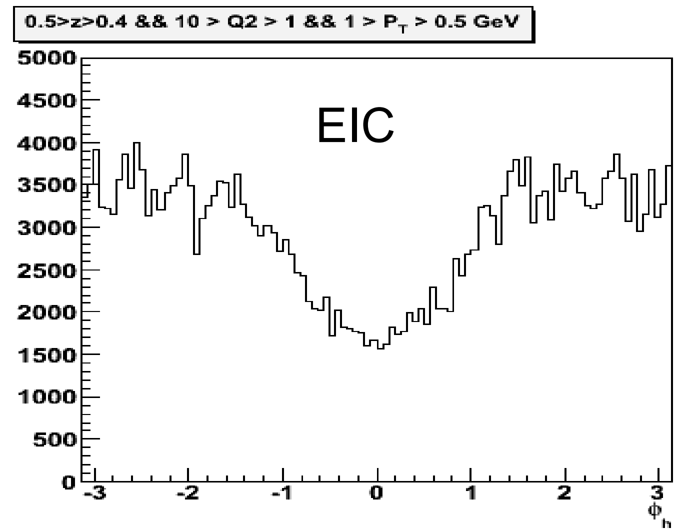
Wide range in Q^2 and P_T accessible with CLAS12 are important for cos2ϕ studies (all background contributions are HT)

Azimuthal moments of A_1 and flavor decomposition



$$Acc_k(\phi_h) = \frac{R_k^{mc}(\phi_h)}{G_k^{mc}(\phi_h)}$$ **azimuthal acceptance**





Acceptance in ϕ (and P_T) may affect the A_1 and flavor decomposition (in particular Δs extractions) in SIDIS?

Summary

- Latest experimental data indicate that quark-gluon/quark correlations leading to spin and azimuthal asymmetries may be very significant

- Measurements of HT are consistent in sign and magnitude for SIDIS experiments at very different energies

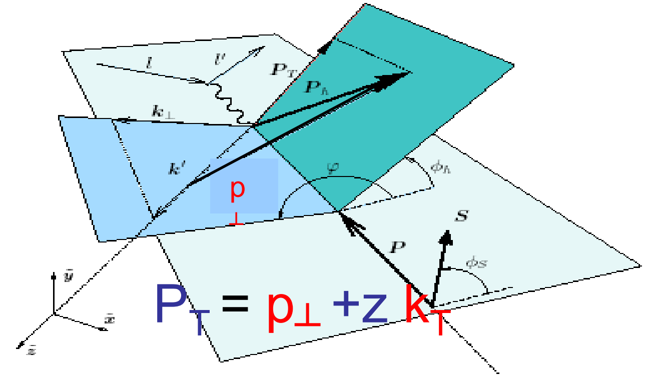
- Higher Twist distributions are accessible in single and double spin azimuthal asymmetries, can be calculated in models and lattice

- Di-hadron production provide exciting possibility to measure HT functions in model independent way within collinear factorization

- Higher twists are indispensable part of SIDIS analysis and their understanding is crucial for interpretation of SIDIS leading twist observables

Support slides….

FAST-MC for CLAS12



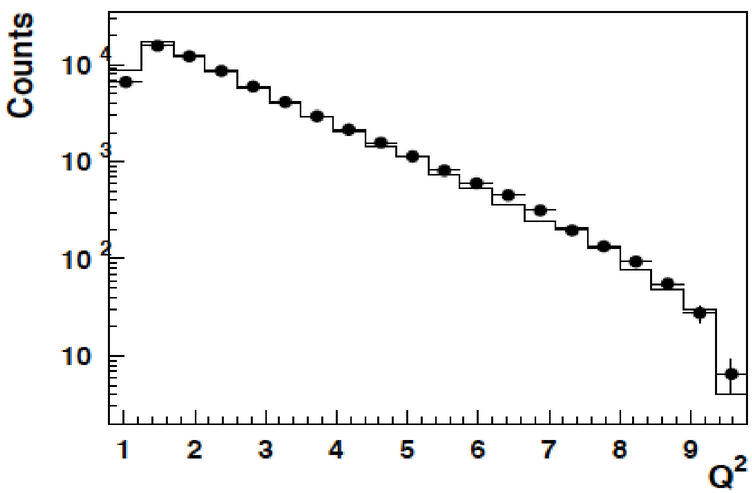
SIDIS MC in 8D ($x,y,z,\phi,\phi_S,p_T,\lambda,\pi$)

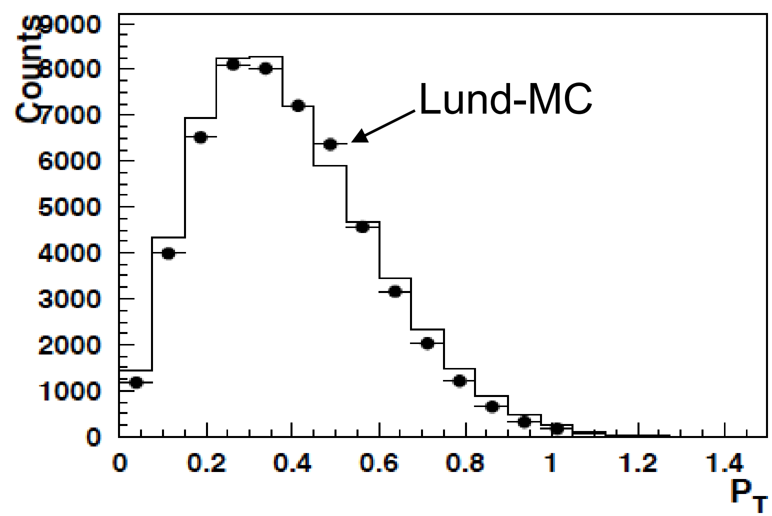
Simple model with 10% difference between f1 ($0.2 GeV^2$) and g1 widths with a fixed width for D1 ($0.14 GeV^2$)

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

CLAS12 acceptance & resolutions

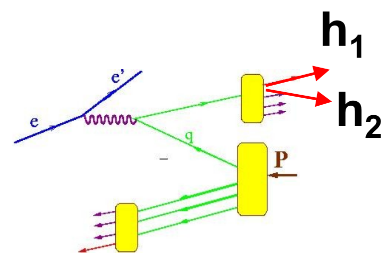
Events in CLAS12





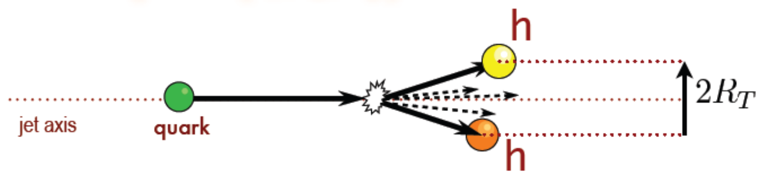
Reasonable agreement of kinematic distributions with realistic LUND simulation

Hadronization in current and target regions

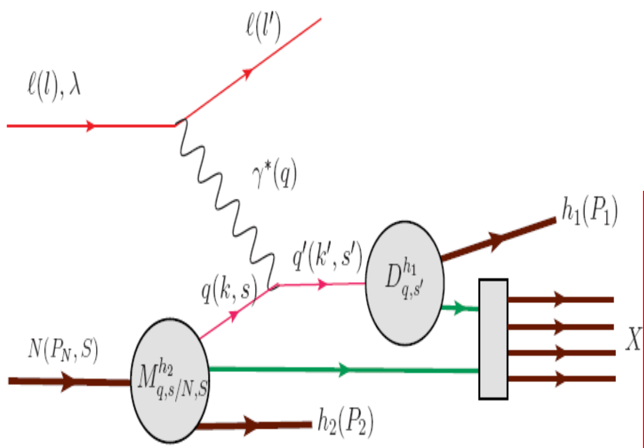


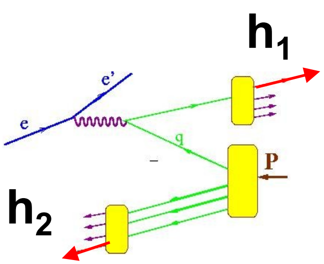
✦ DiFF

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



Collinear factorization



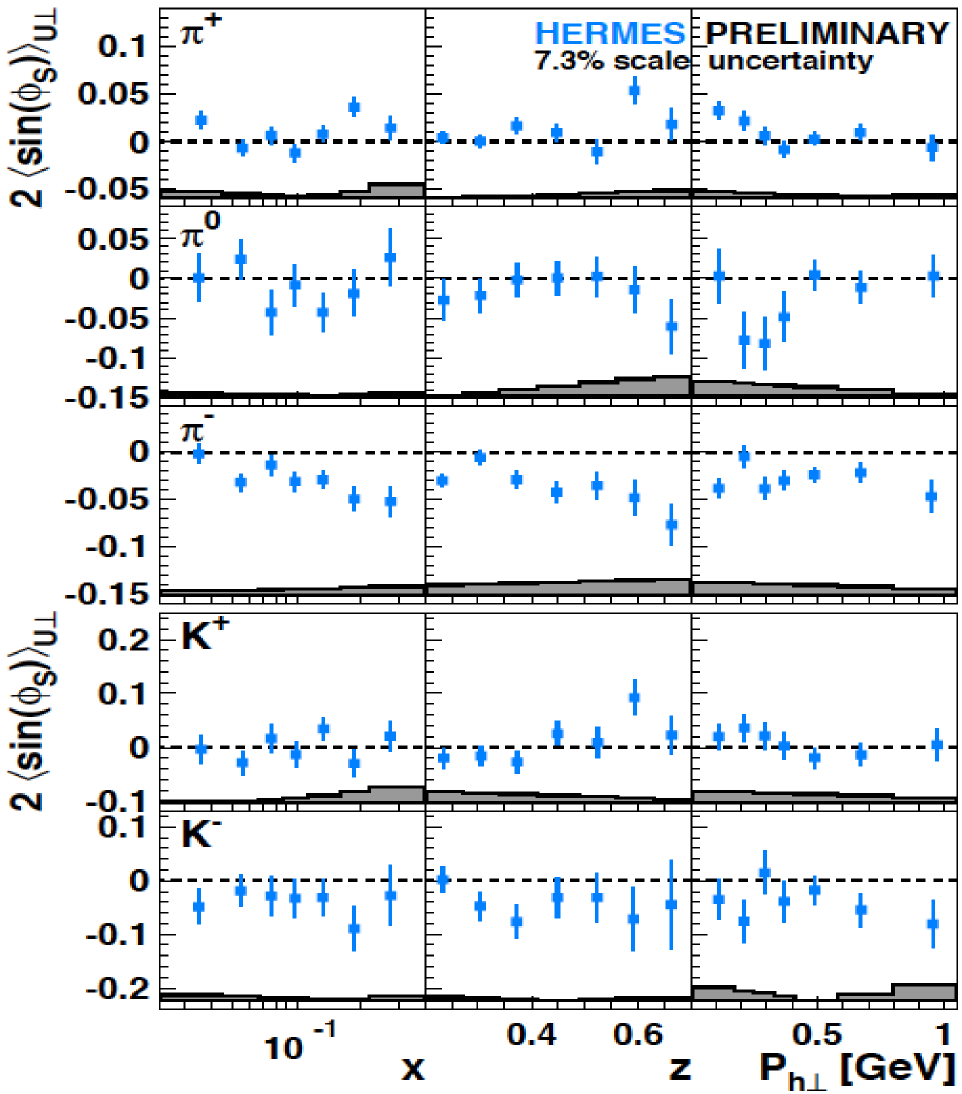


Anselmino/Barone/Kotzinian
arXiv:1107.2292 (2011)

Fracture Function:
conditional probabilities to find a quark with certain polarization and longitudinal momentum fraction xB and transverse momentum k_T inside a nucleon fragmenting into a hadron carrying a fraction z of the nucleon longitudinal momentum and a transverse momentum P_T

$$\sigma_{LU} = -\frac{P_{T1}P_{T2}}{m_2 m_N} F_{k1}^{\Delta\hat{g}_1^{\perp h}\cdot D_1} \sin(\phi_1-\phi_2)\,.$$

HT effects with transverse target



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

$$f_T D_1 - \frac{M_h}{M} x h_T H_1^{\perp}$$

Higher Twist SSAs

Target sinϕ SSA (Bacchetta et al. 0405154)

Discussed as main sources of SSA due to the Collins fragmentation

$$A_{\rm UL}^{\sin\phi} \approx \frac{2(2-y)\sqrt{1-y}}{(1-y+y^2)f_1D_1}\frac{zMM_h}{Q}\left[-\frac{M}{M_h}xf_L^{\perp(1)}D_1 - xh_LH_1^{\perp(1)} - \frac{M_h}{M}g_1\frac{G^{\perp(1)}}{z} - \cancel{h_{1L}^{\perp(1)}\frac{\tilde{H}}{z}}\right]$$

In jet SIDIS only contributions ~ D_1 survive

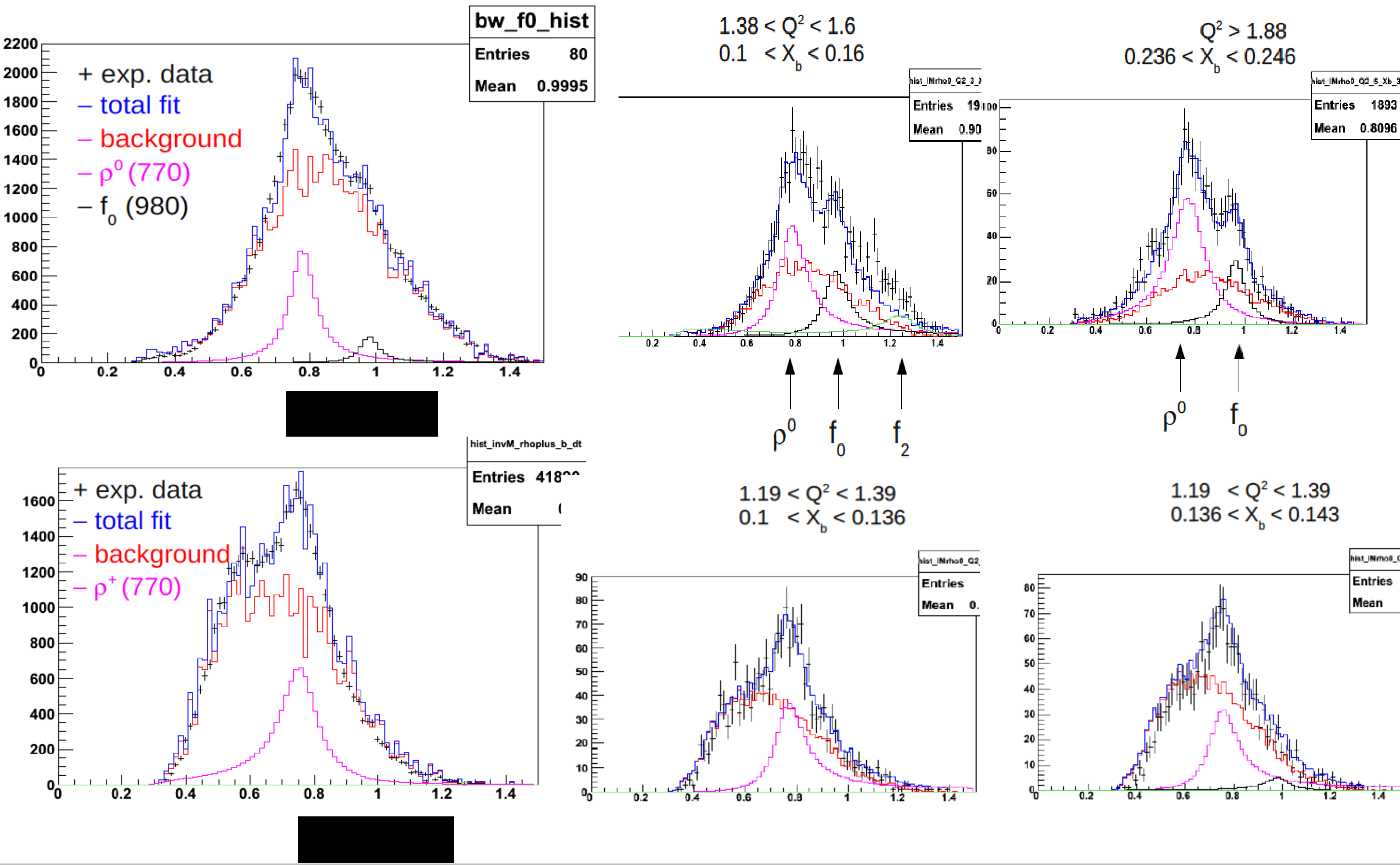
The same unknown fragmentation function

Beam sinϕ SSA

$$A_{\rm LU}^{\sin\phi} \approx \frac{2y\sqrt{1-y}}{(1-y+y^2)f_1D_1}\frac{zMM_h}{Q}\left[\frac{M}{M_h}xg^{\perp(1)}D_1 + xeH_1^{\perp(1)} + \frac{M_h}{M}f_1\frac{G^{\perp(1)}}{z} - \cancel{h_1^{\perp(1)}\frac{E}{z}}\right]$$

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

Dihadron simulations with LUND-MC @6 GeV



[redacted]

[redacted]

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	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

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

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

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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	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{UU}^{\cos\phi} \sim -h_1^\perp \frac{H}{z} + x h H_1^\perp$$

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	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

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

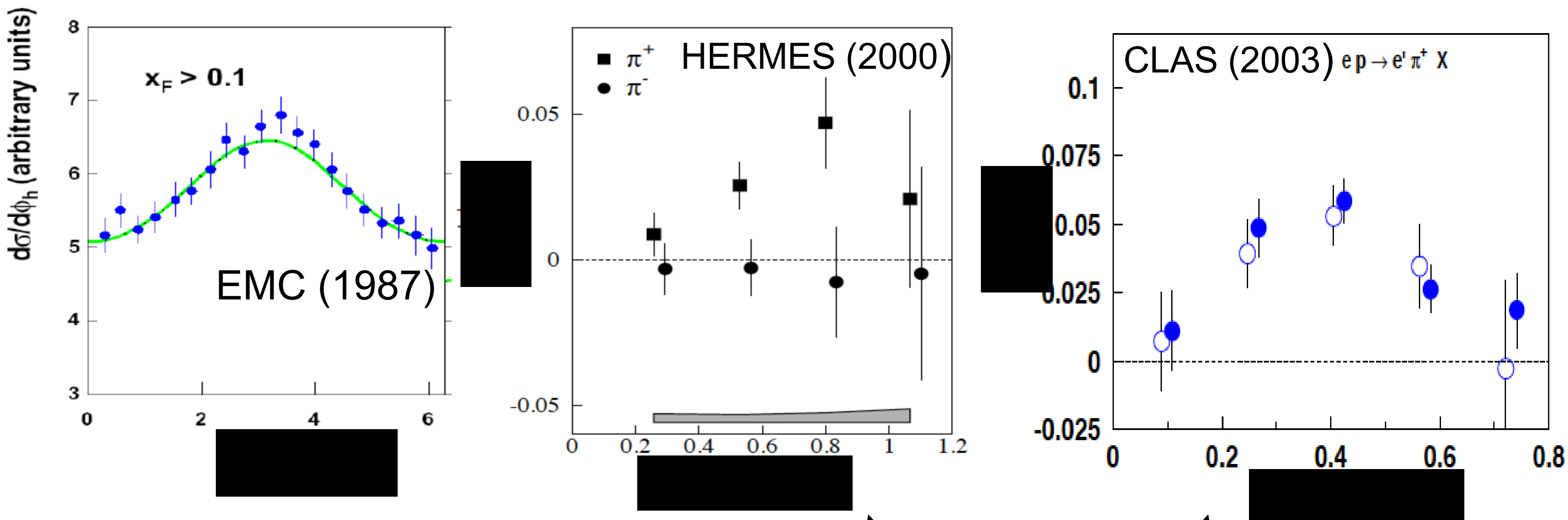
q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

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

Measurements of SS azimuthal asymmetries in SIDIS

[redacted]

Large cosϕ and sinϕ modulations have been observed in electroproduction of hadrons in SIDIS with polarized and unpolarized targets



Related to spin-orbit correlations in fragmentation?

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	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{\mathrm{LU}}^{\sin\phi} \sim h_1^\perp \frac{E}{z} + x e H_1^\perp$$

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 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	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

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

q/h	U	L	T
U	$D_1^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
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	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

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

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	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

SSA with transversely 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	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$f_T D_1 - \frac{M_h}{M} x h_T H_1^\perp$$

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	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

Twist-3 PDFs : "new testament"

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

$$\frac{1}{2Mx}\,\mathrm{Tr}\left[\tilde{\Phi}_{A\alpha}\,\sigma^{\alpha+}\right] = \tilde{h} + i\,\tilde{e} + \frac{\epsilon_T^{\rho\sigma}\,p_{T\rho}S_{T\sigma}}{M}\,(\tilde{h}_T^{\perp} - i\,\tilde{e}_T^{\perp}),$$

$$\frac{1}{2Mx}\,\mathrm{Tr}\left[\tilde{\Phi}_{A\alpha}\,i\sigma^{\alpha+}\gamma_5\right] = S_L\,(\tilde{h}_L + i\,\tilde{e}_L) - \frac{p_T\cdot S_T}{M}\,(\tilde{h}_T + i\,\tilde{e}_T),$$

$$\frac{1}{2Mx}\,\mathrm{Tr}\left[\tilde{\Phi}_{A\rho}(g_T^{\alpha\rho} + i\epsilon_T^{\alpha\rho}\gamma_5)\gamma^+\right] = \frac{p_T^{\alpha}}{M}(\tilde{f}^{\perp} - i\tilde{g}^{\perp}) - \epsilon_T^{\alpha\rho}\,S_{T\rho}\,(\tilde{f}_T + i\tilde{g}_T)$$

$$- S_L\,\frac{\epsilon_T^{\alpha\rho}\,p_{T\rho}}{M}\,(\tilde{f}_L^{\perp} + i\,\tilde{g}_L^{\perp}) - \frac{p_T^{\alpha}\,p_T^{\rho} - \frac{1}{2}\,p_T^2\,g_T^{\alpha\rho}}{M^2}\,\epsilon_{T\rho\sigma}\,S_T^{\sigma}\,(\tilde{f}_T^{\perp} + i\tilde{g}_T^{\perp}),$$

$$\boxed{\frac{e^{u-d}}{f_1^{u-d}}}$$ a higher twist result from straight links

$\Phi^{[1]} = \frac{m_N}{P^+} e$. (The T-odd term vanishes for straight links)

$\tilde{\Phi}^{[1]} = 2 m_N \tilde{A}_1$

$$\Rightarrow \Phi^{[1]} = \int \frac{d(\ell\cdot P)}{(2\pi)} e^{-ix(\ell\cdot P)} \int \frac{d^2\vec{\ell}_\perp}{(2\pi)^2} e^{i\vec{\ell}_\perp\cdot\vec{k}_\perp} \frac{1}{P^+} \cdot 2 m_N \tilde{A}_1 \Big|_{\ell^+=0}$$

$$= \frac{m_N}{P^+} e$$

$$\Rightarrow \quad e = \int \frac{d(\ell\cdot P)}{2\pi} e^{-ix(\ell\cdot P)} \int \frac{d^2\ell_\perp}{(2\pi)^2} e^{i\vec{\ell}_\perp\cdot\vec{k}_\perp} 2\tilde{A}_1 \Big|_{\ell^+=0}$$

$$\int dx \; e = \int \frac{d^2\ell_\perp}{(2\pi)^2} e^{i\vec{\ell}_\perp\cdot\vec{k}_\perp} 2\tilde{A}_1(\underset{-\vec{\ell}_\perp^{\,2}}{\ell^2}, \underset{0}{\ell\cdot P}) \Big|_{\substack{\ell^+=0\\ \ell\cdot P=0}}$$

$$\int d^2\ell_\perp \, e^{-i\vec{\ell}_\perp\cdot\vec{k}_\perp} e(x,\vec{k}_\perp^{\,2}) = 2\tilde{A}_1(-\vec{\ell}_\perp^{\,2}, 0)$$

use $\ell = -b$

$$\boxed{e^{[1]}(\vec{b}_\perp^{\,2}) = \int_{-1}^{1} dx \; e(x,\vec{b}_\perp^{\,2}) = 2\tilde{A}_1(-\vec{b}_\perp^{\,2}, 0)}$$

so $$\boxed{\frac{e^{[1]}(\vec{b}_\perp^{\,2})}{f_1^{[1]}(\vec{b}_\perp^{\,2})} = \frac{\tilde{A}_1}{\tilde{A}_2}}$$

Studies of Dihadron Electroproduction in DIS with Unpolarized and Longitudinally Polarized Hydrogen and Deuterium Targets

Harut Avakian (JLab)

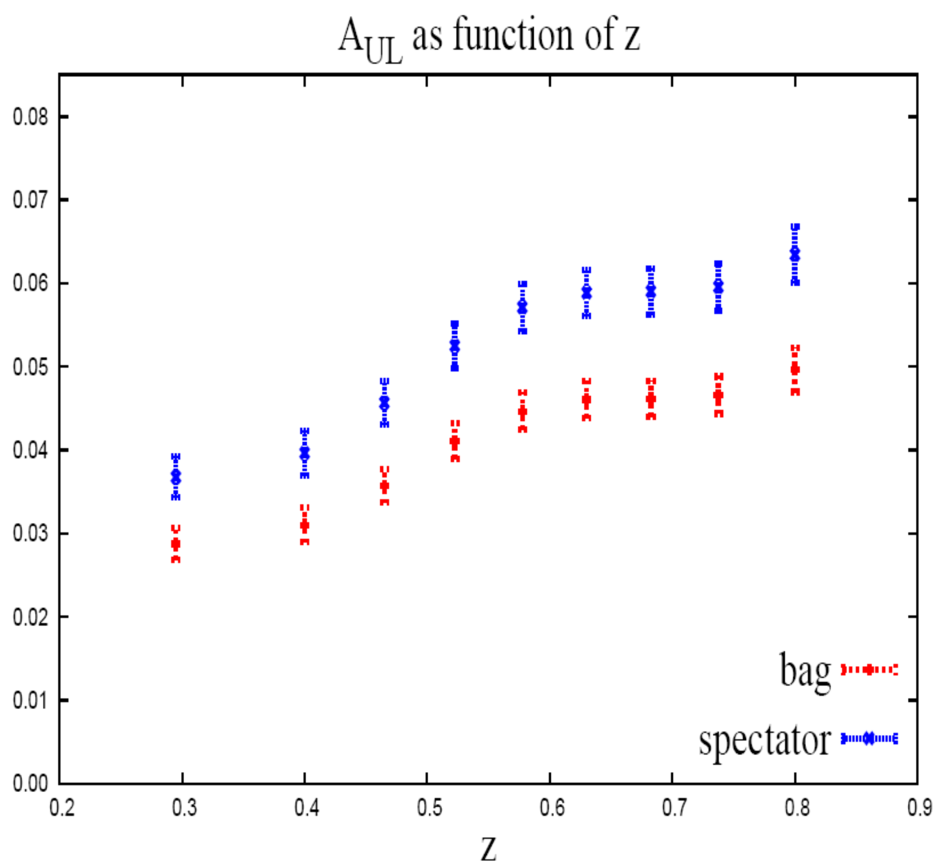
JLab PAC38, Aug 24, 2011

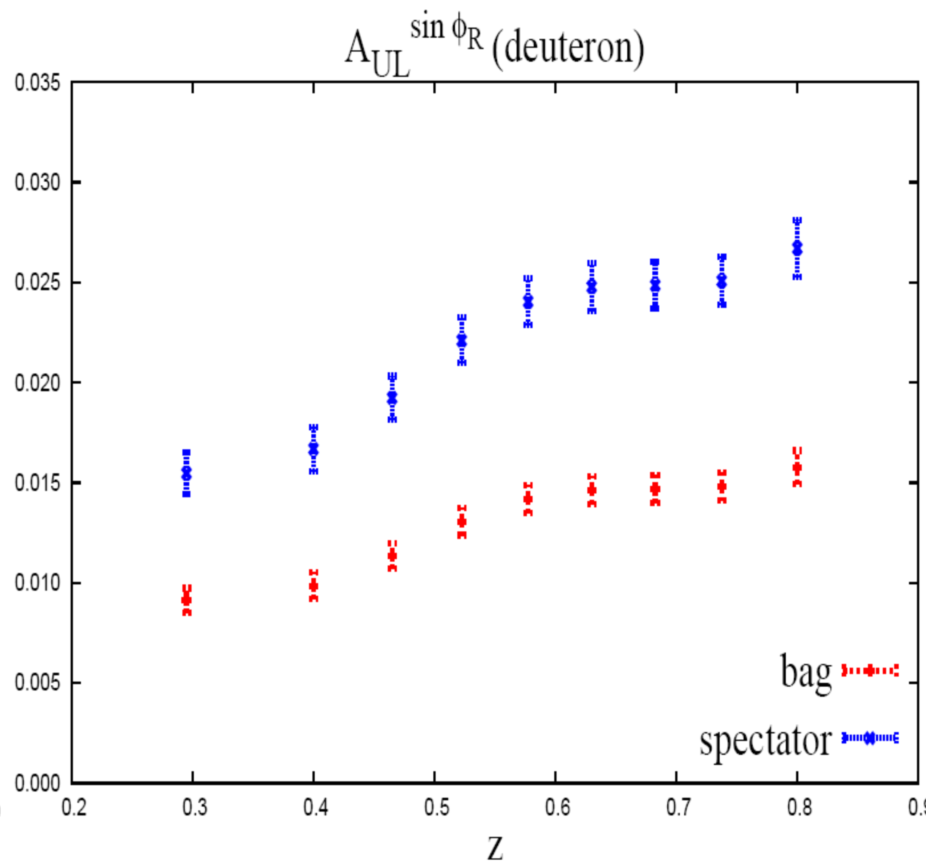
Proposal PR12-11-109

- Measure hadron pairs in current and target fragmentation regions
- Study higher-twist distribution functions and interference effects in hadronization

Spokespersons: S. Anefalos-Pereira (LNF-INFN) , H. Avakian (JLab), A. Courtoy (U. Pavia)
K. Griffioen (W&M), L. Pappalardo (INFN-Ferrara)

Model predictions: polarized target



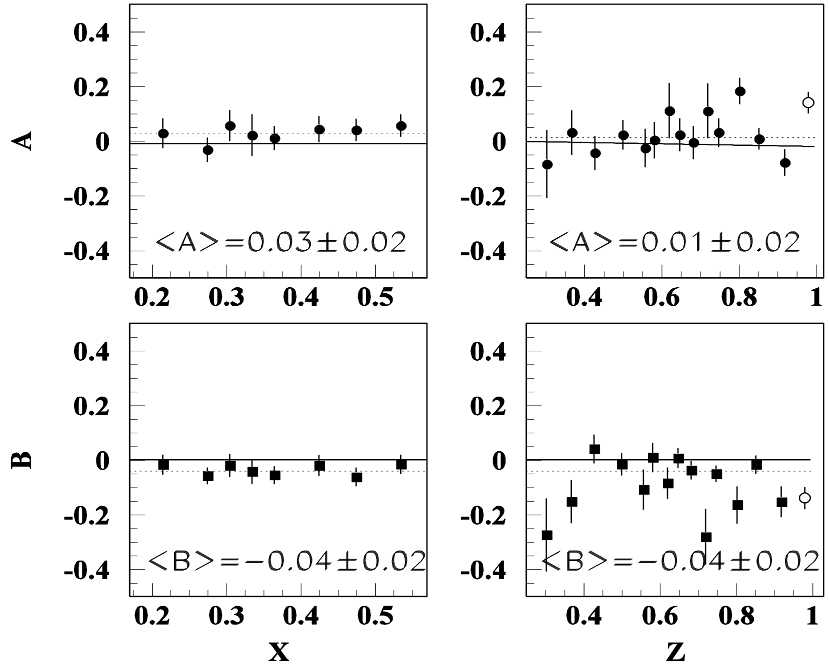


- Models agree on a large target SSA for $\pi\pi$ pair production
- Deuteron target measurements provide complementary information on flavor dependence

The azimuthal terms at low P_t

$$\sigma_{SIDIS}=\sigma_{DIS}\cdot\Sigma e_i^2[q_i(x,Q^2)D_i(z)]\cdot be^{-bp_T^2}\{1+A\cos(\phi)+B\cos(2\phi)\}$$

A and B are the weights of the azimuthal terms (σ_{LT} and σ_{TT})



Solid lines are Cahan theoretical predictions

- $A \sim (P_t/Q)\cdot\xi$
- $B \sim (P_t^2/Q^2)\cdot\xi^2$

Where $\xi = z^2/(1+z^2)$

At $\langle P_t \rangle$ ~0.05 GeV

A ~ B ~ 0 for SIDIS

A and B are much larger in exclusive pion production (open symbols)

- No significant difference between the results for π^- or π^+, or H and D.
- At low P_t the azimuthal dependence is consistent with zero.