TMD measurements at CLAS

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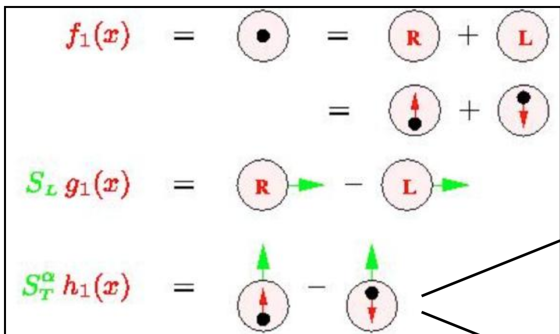
Outline

Transverse structure of the nucleon and partonic correlations

- Introduction
- Hard scattering processes and correlations between spin and transverse degrees of freedom
- k_T-effects with polarized SIDIS
- Higher twist effects in SIDIS
- Summary

Structure of the nucleon

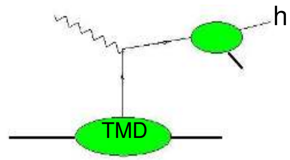
PDFs, q(x): Probabilities to find a quark with a fraction x of proton momentum P

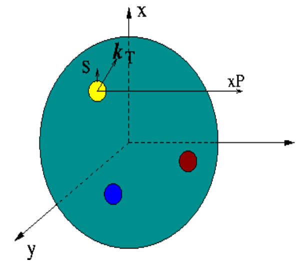


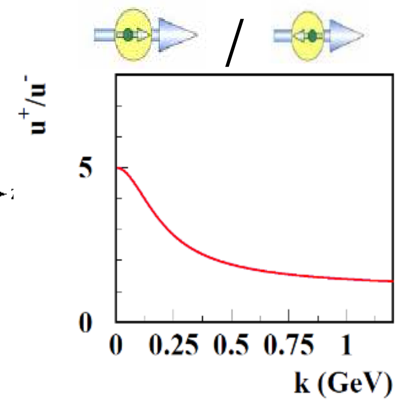
$h_1(x, \vec{k}_T)$

$H_T(x, \vec{r}_T)$

Semi-Inclusive processes and transverse momentum distributions

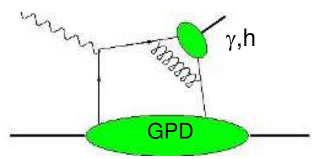


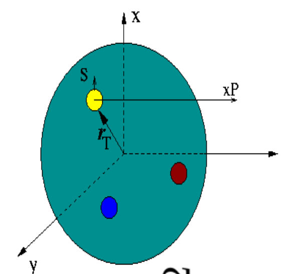


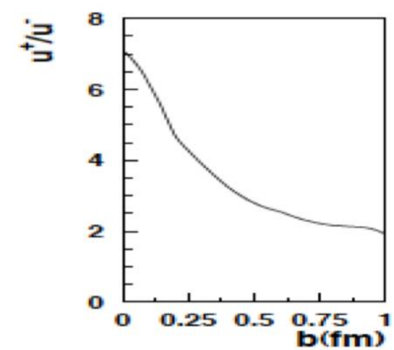


B.Pasquini et al

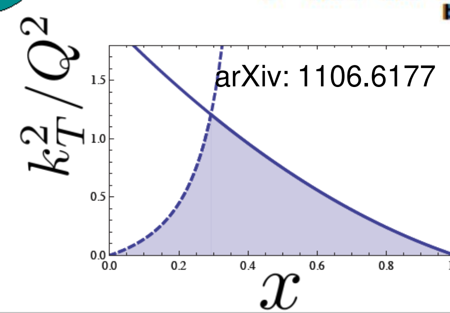
Hard exclusive processes and spatial distributions of partons







Detection of final state particles in semi-inclusive and hard exclusive processes allows access also to transverse distribution of quarks.

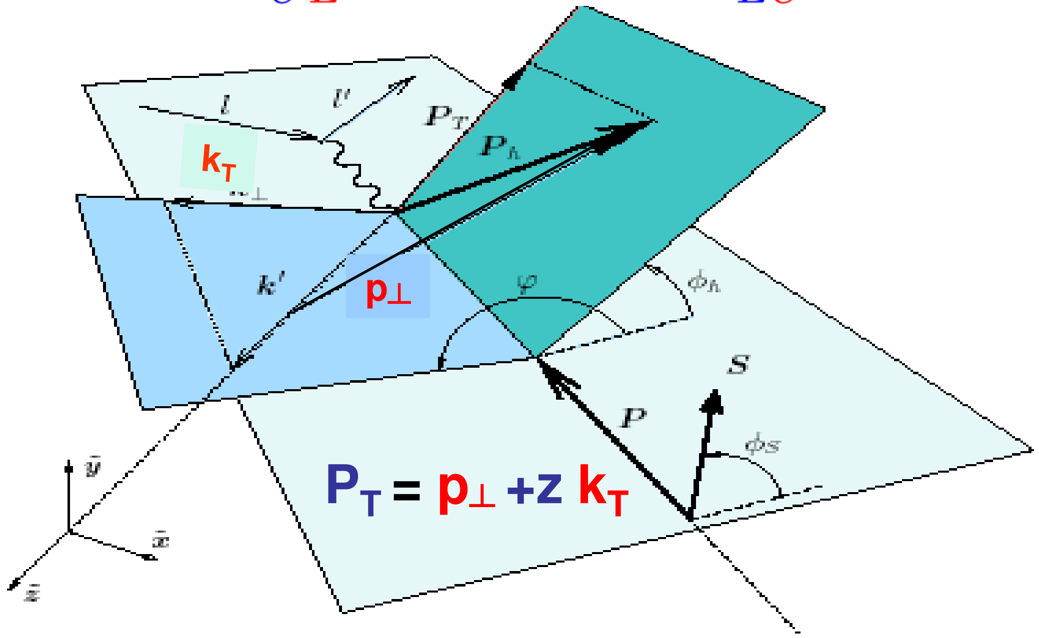


Collinear analysis of observables in semi-inclusive and hard exclusive processes will be sensitive to integration region over transverse degrees of freedom due to correlations of x, spin and transverse degrees of freedom.

SIDIS: partonic cross sections

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

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



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

$$d\sigma^{\gamma^* H \to hX} \propto \sum e_q^2 \int d^2\vec{k}_T d^2\vec{p}_\perp f^{H\to q}(x, \vec{k}_T) D^{q\to h}(z, \vec{p}_\perp)\delta^{(2)}(z\vec{k}_T + \vec{p}_\perp - \vec{P}_T)$$

$$\downarrow$$

$$d\sigma^h \propto \sum f^{H\to q}(x) \mathrm{d}\sigma_q(y) D^{q\to h}(z)$$

Azimuthal moments in SIDIS

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \;& \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{ F_{UU,T} + \varepsilon\, F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\, F_{UU}^{\cos\phi_h} \\
& + \varepsilon\cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\, F_{LU}^{\sin\phi_h} \\
& + S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\, F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h}\right] \\
& + S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\, F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\, F_{LL}^{\cos\phi_h}\right] \\
& + |\boldsymbol{S}_\perp|\left[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)\right. \\
& + \varepsilon\,\sin(\phi_h+\phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} \\
& \left. + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)}\right] \\
& + |\boldsymbol{S}_\perp|\lambda_e\left[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\, F_{LT}^{\cos\phi_S}\right. \\
& \left. + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)}\right]\Big\},
\end{aligned}
$$

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}	$\mathbf{h_1}$ $h_{1T}^\perp$

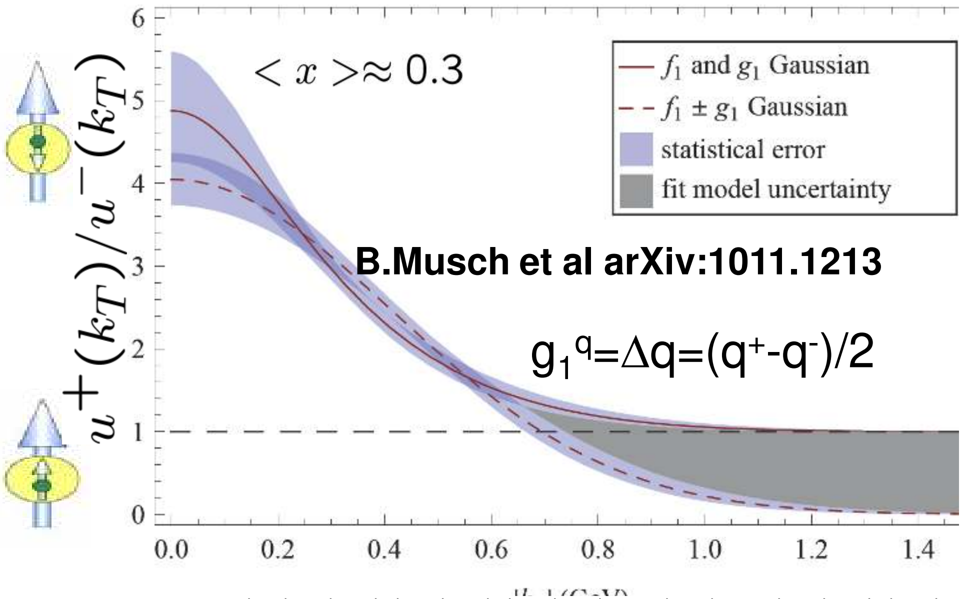
Higher Twist PDFs

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

$D_1^{q\to h}$ | $H_1^{\perp q\to h}$

Experiment for a given target polarization measures all moments simultaneously

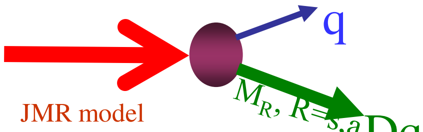
Quark distributions at large k_T: lattice



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

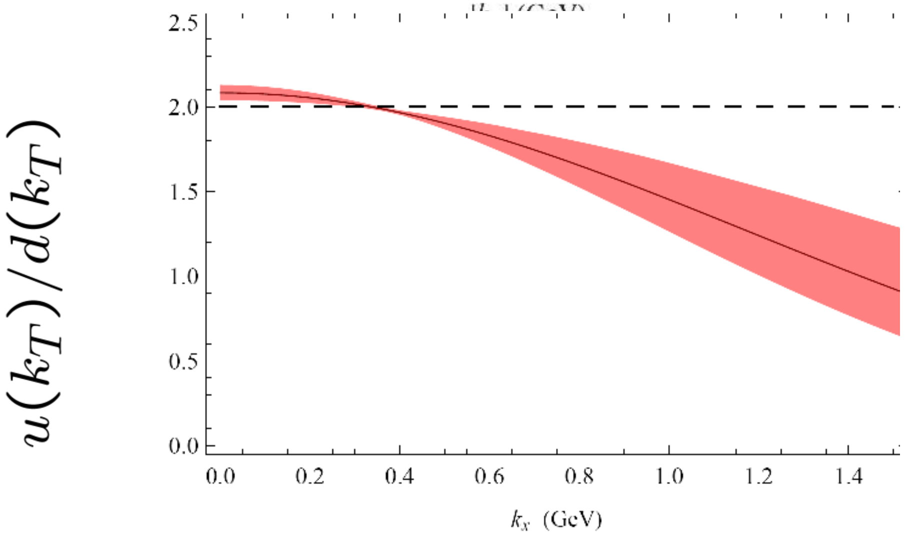
$$g_1^q(x, k_T) = g_1(x)\frac{1}{\pi\mu_2^2}\exp\left(-\frac{k_T^2}{\mu_2^2}\right)$$

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



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

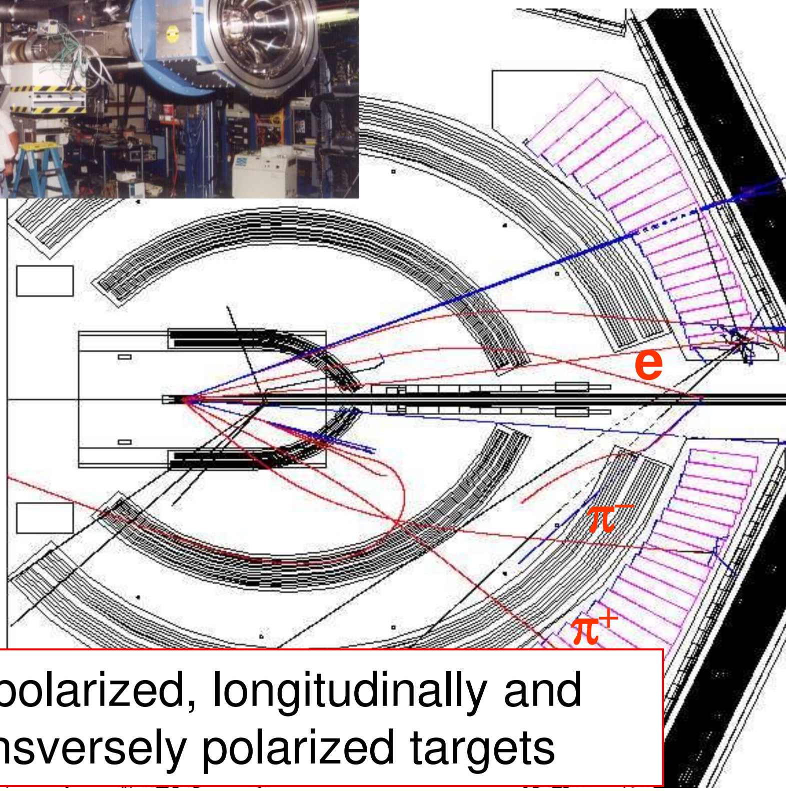
$$u^-(x, k_T^2) \propto \frac{k_T^2}{(k_T^2 + \lambda_R^2)^{2\alpha}},$$



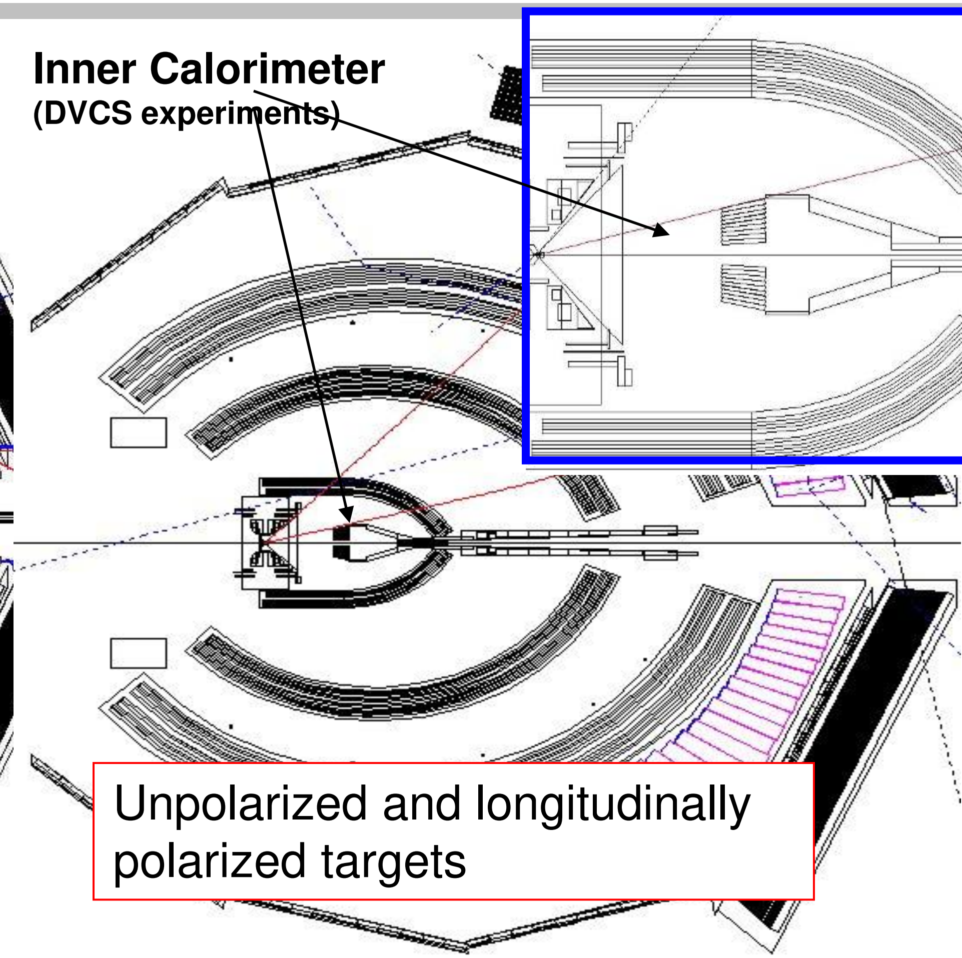
Higher probability to find a d-quark with at large k_T

k_T-distributions of TMDs may depend on flavor and spin

ep→e' πX CLAS configurations



Unpolarized, longitudinally and transversely polarized targets



Unpolarized and longitudinally polarized targets

- Polarized NH3/ND3 (no IC, ~5 days)
- Unpolarized H (with IC ~ 60 days)
- Polarized NH3/ND3 with IC 60 days
  10% of data on carbon
- Polarized HD-Ice (no IC, 25 days)

➢**Polarizations:**
➢**Beam: ~80%**
➢**NH3 proton 80%,ND3 ~30%**
➢**HD (H-75%,D-25%))**

$A_1 - P_T$ 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 $h_{1T}^\perp$

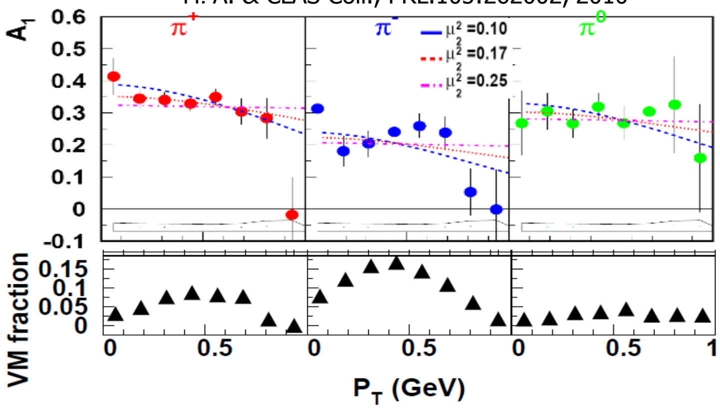
$$A_1(x,z,P_T) = A_1(x,z)\frac{\langle P_T^{2,unp}\rangle}{\langle P_T^{2,pol}\rangle}\exp(-P_T^2/\langle P_T^{2,pol}\rangle - P_T^2/\langle P_T^{2,unp}\rangle)$$

M. Anselmino et al PRD74:074015, 2006

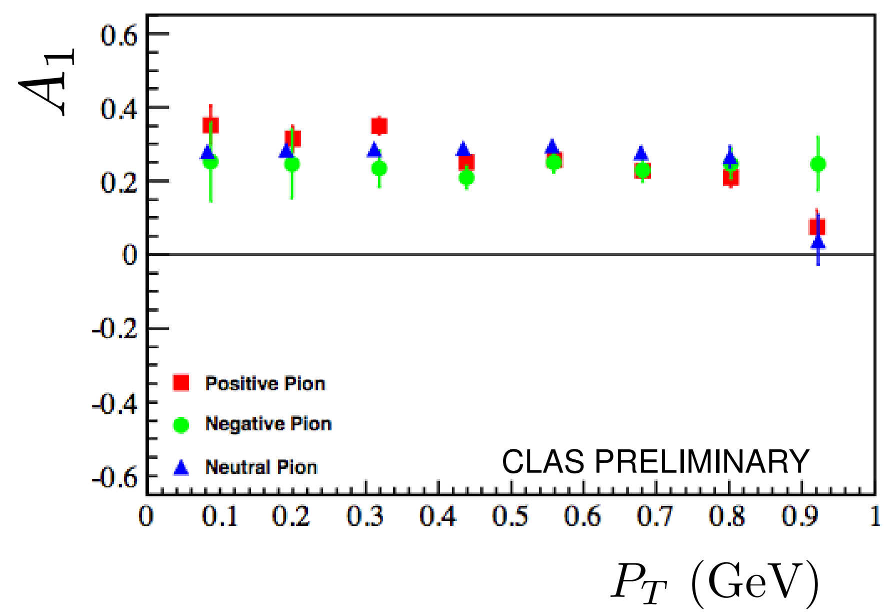
μ_0^2=0.25GeV^2
μ_D^2=0.2GeV^2

0.4<z<0.7

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



S. Skoirala



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

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

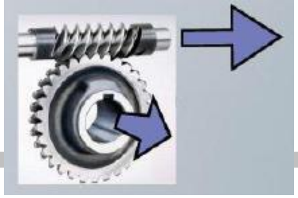
$$< P_T^2(z) >= z^2\mu_{0/2}^2 + \mu_D^2$$

B.Musch et al arXiv:1011.1213

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

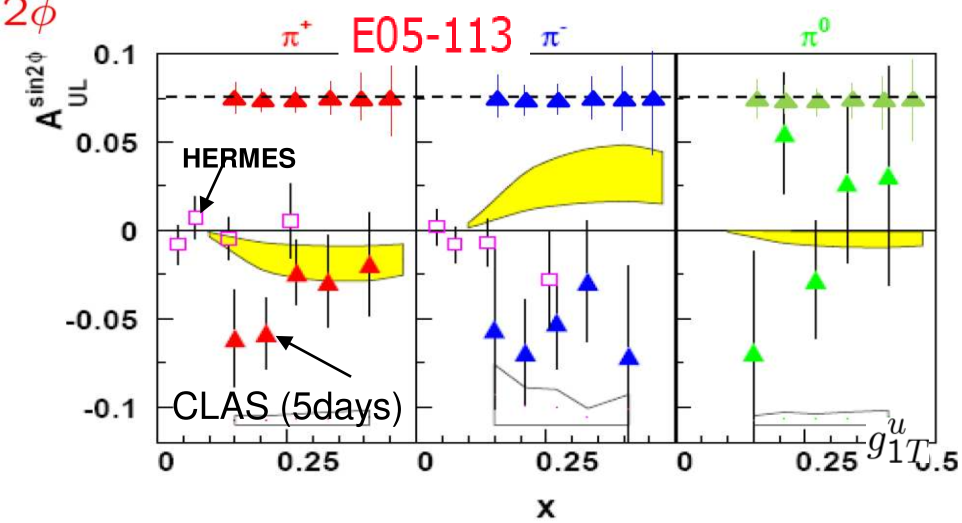
π^+ A_1 suggests broader k_T distributions for f_1 than for g_1
The new data is consistent with old measurements, now available in several bins in x

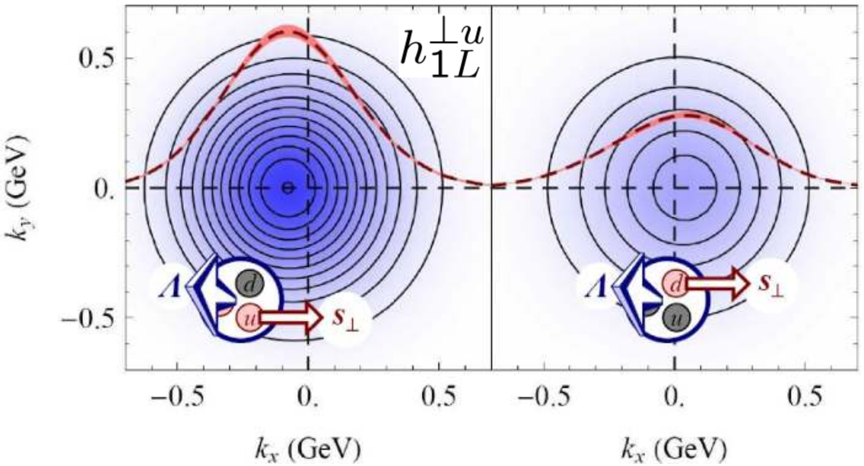
Kotzinian-Mulders Asymmetries



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

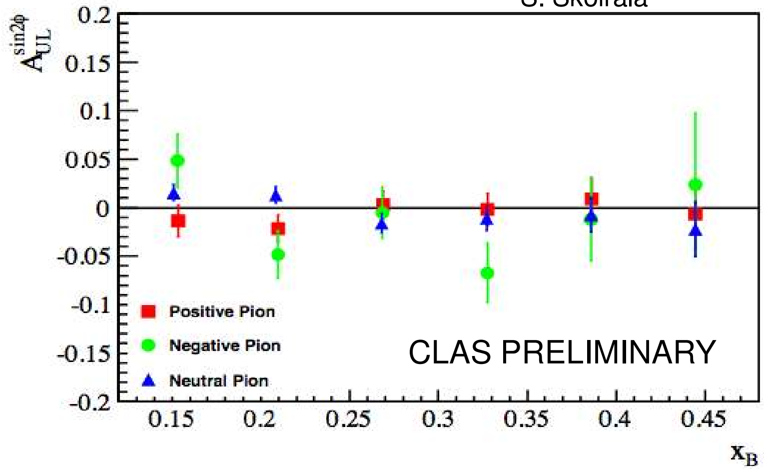
N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$





B.Musch arXiv:0907.2381

S. Skoirala

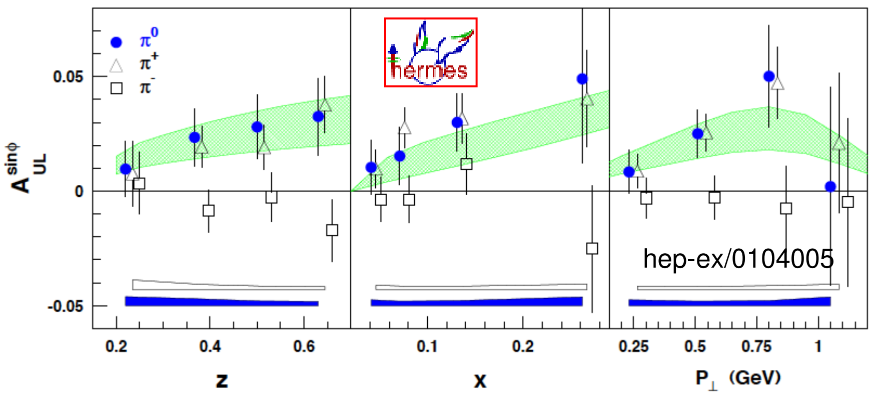


Worm gear TMDs are unique (no analog in GPDs)

Logitudinally polarized Target SSA

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

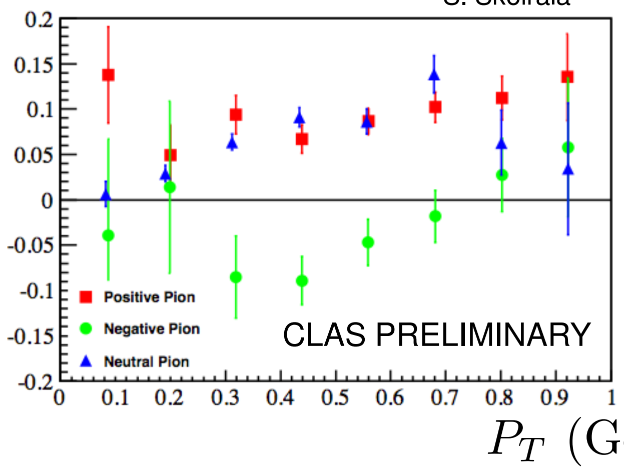
N/q	U	L	T
L			h_L

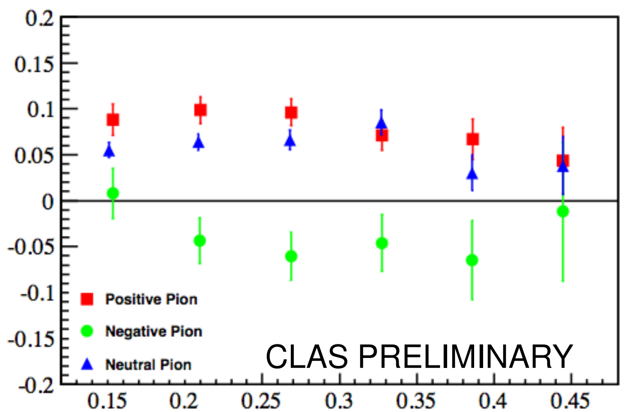


$$A_{UL}^{Collins} \sim h_L H_1^\perp$$

Kotzinian et al (1999)

S. Skoirala





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

The sinϕ moments of π^0 and π^+ of target SSA comparable, while
π– SSA seem to have an opposite to $\pi^{0/+}$ sign at CLAS (also HERMES)

Longitudinally Polarized Beam SSA

$$A_{LU}(\phi) = \frac{1}{P_b}\frac{N^+ - N^-}{N^+ + N^-}$$

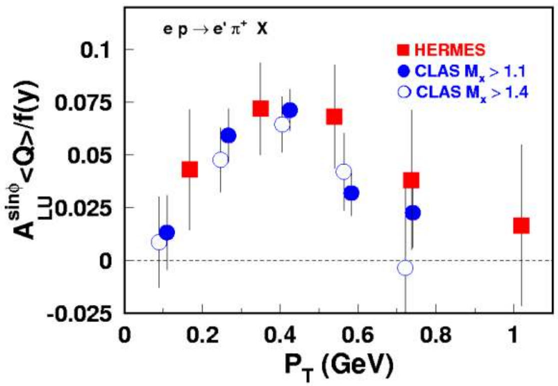
HT function related to force on the quark. Burkardt (2008),Qiu(2011)

N/q	U	L	T
U			e

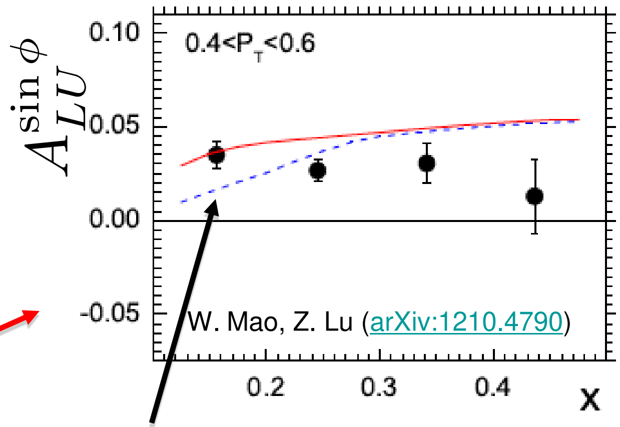
$A_{LU}^{Collins} \sim eH_1^{\perp}$

Efremov et al (2003)

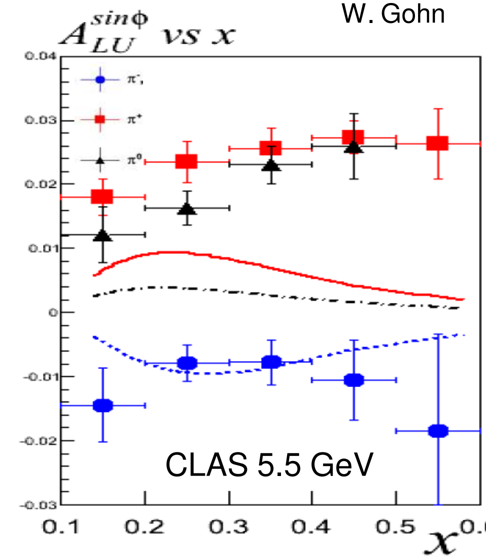
A_{LU} CLAS @4.3 GeV (2003)



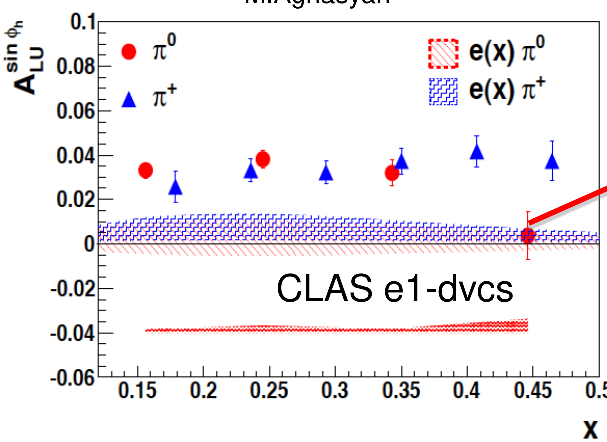
$g^{\perp} D_1$



W. Gohn



M.Aghasyan

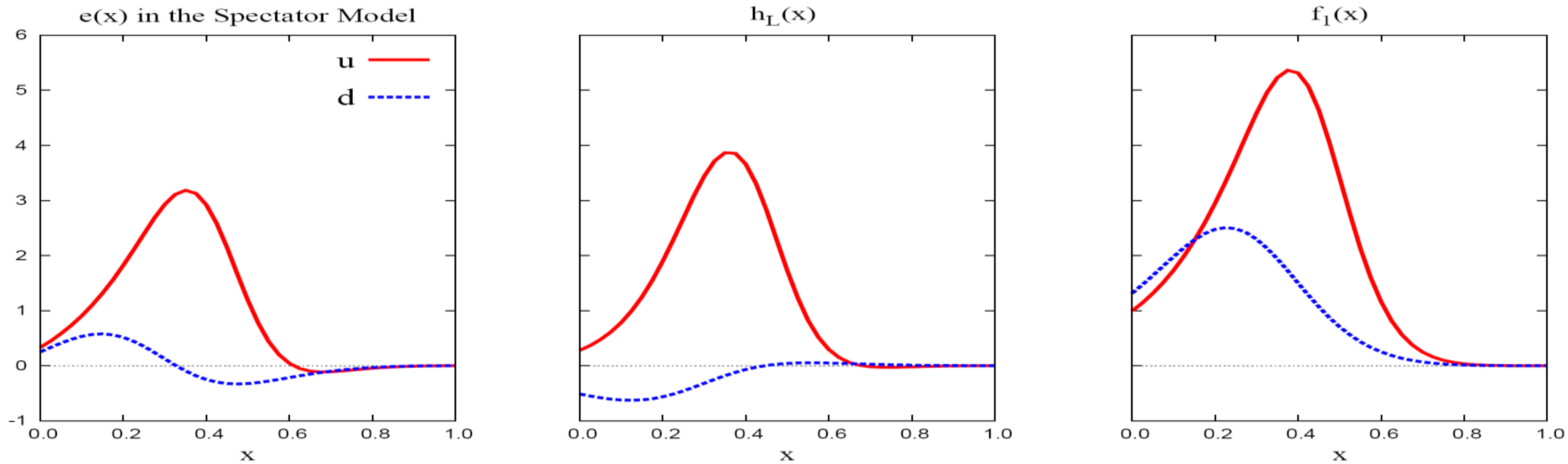


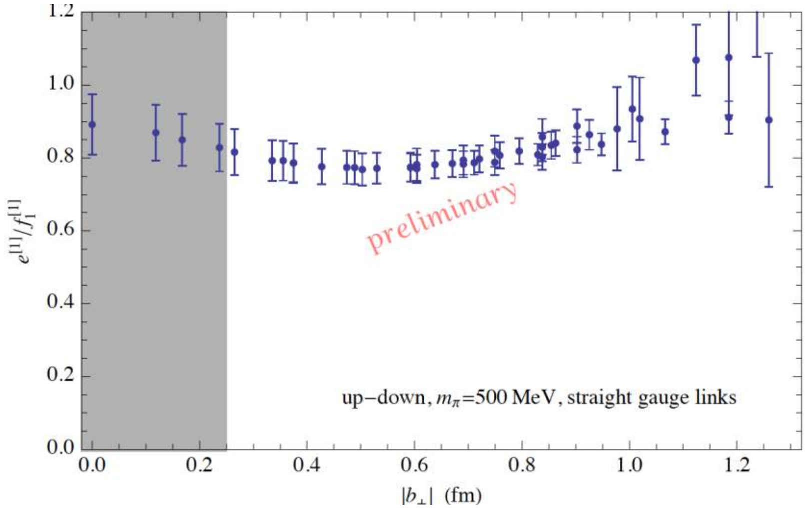
x vs k_T correlations matter

Sivers type contribution may be dominant for π^0

Collins type contribution may be dominant for π-

Model predictions: unpolarized target





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

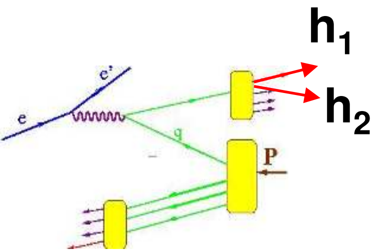
$$f_1^{[1]}(\boldsymbol{k}_\perp^2) \equiv \int_{-1}^{1} dx\ f_1(x, \boldsymbol{k}_\perp^2)$$

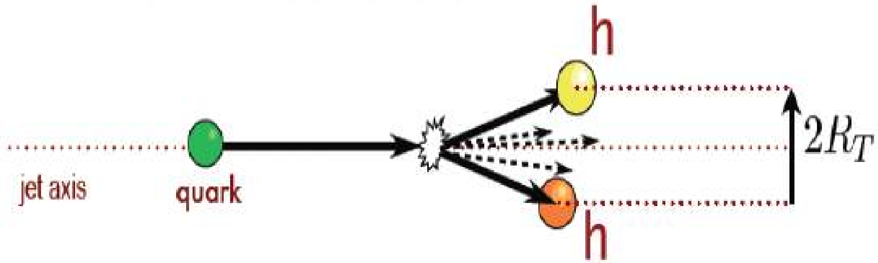
$$\frac{e^{[1]}}{f_1^{[1]}} = \frac{\tilde{A}_1}{\tilde{A}_2}$$

- Models agree on a large beam SSA for ππ pair production
- Lattice results for u-d can be directly compared to models and data.

Dihadron production kinematics

z_1, z_2 - fractions of energy carried by a hadrons

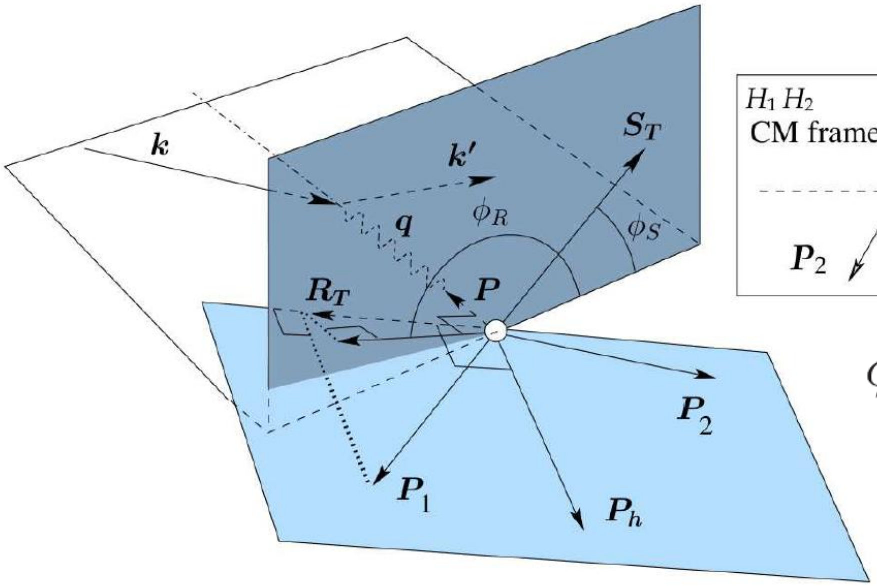


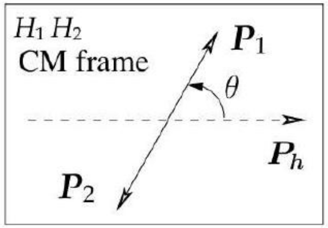


DiFF

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

- Factorization proven
- Evolution known
- Extracted at BELLE for $\pi\pi$ pairs, planned for πK pairs





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

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

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

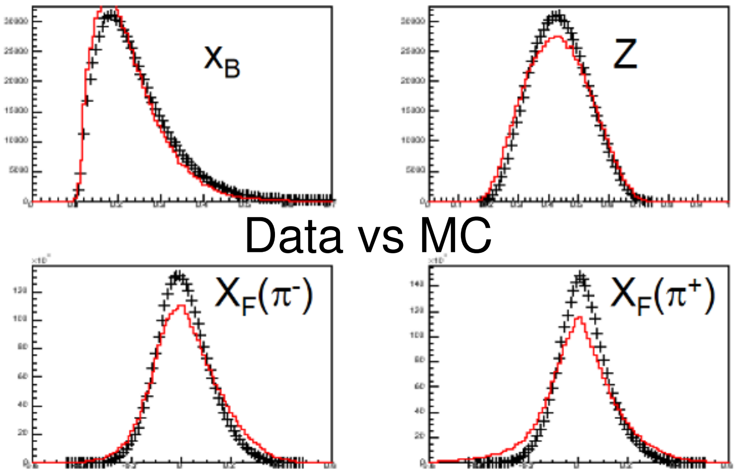
Dihadron productions offers exciting possibility to access HT pdfs as we deal with the product of functions instead of convolution

Dihadron production kinematics

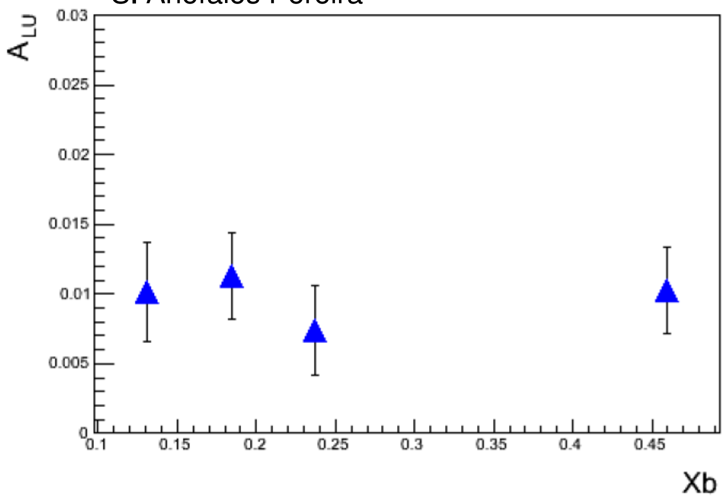
$$F_{LU}^{\sin\phi_R} = -x\frac{|R|\sin\theta}{Q}\left[\frac{M}{M_h}\,x\,e^q(x)\,H_1^{\sphericalangle q}(z,\cos\theta,M_h) + \frac{1}{z}\,f_1^q(x)\,\widetilde{G}^{\sphericalangle q}(z,\cos\theta,M_h)\right],$$

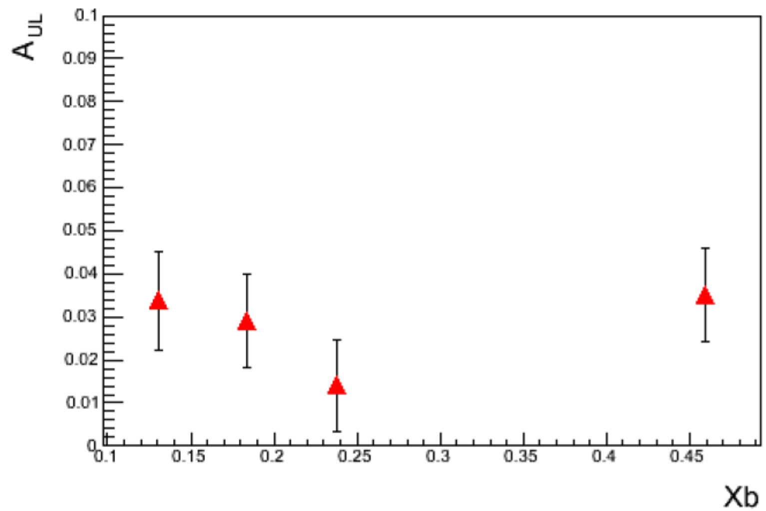
$$F_{UL}^{\sin\phi_R} = -x\frac{|R|\sin\theta}{Q}\left[\frac{M}{M_h}\,x\,h_L^q(x)\,H_1^{\sphericalangle q}(z,\cos\theta,M_h) + \frac{1}{z}\,g_1^q(x)\,\widetilde{G}^{\sphericalangle q}(z,\cos\theta,M_h)\right]$$

$$F_{UU,T} = x f_1^q(x)\,D_1^q(z,\cos\theta,M_h)$$

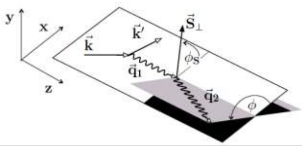


S. Anefalos Pereira

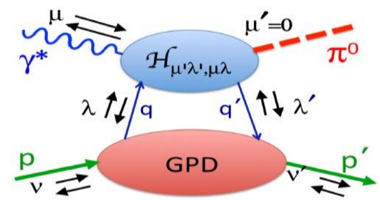




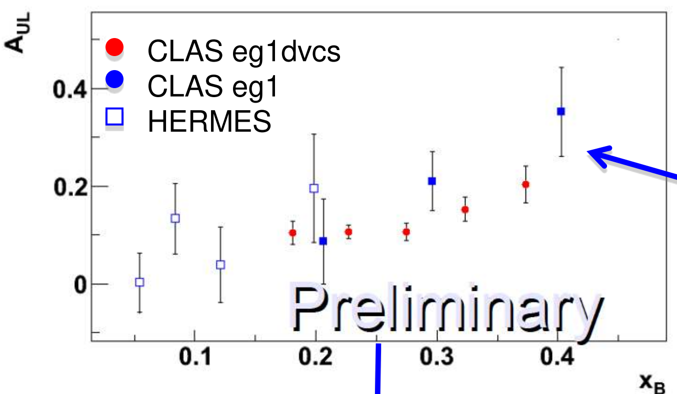
Dihadron productions offers exciting possibility to access HT parton distribution surviving k_T-integration



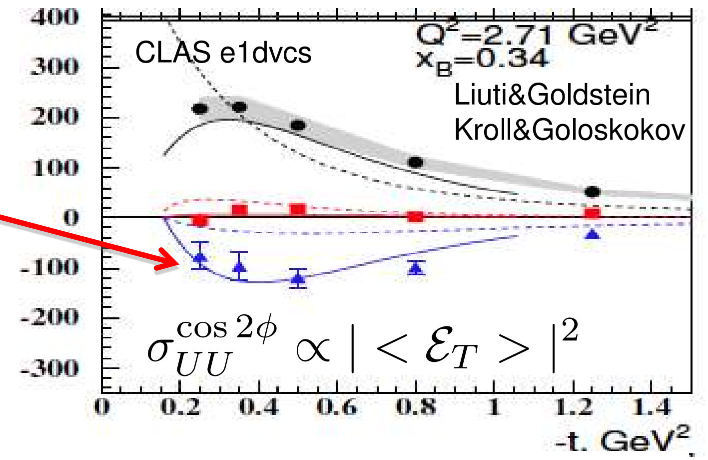
3D structure: GPDs

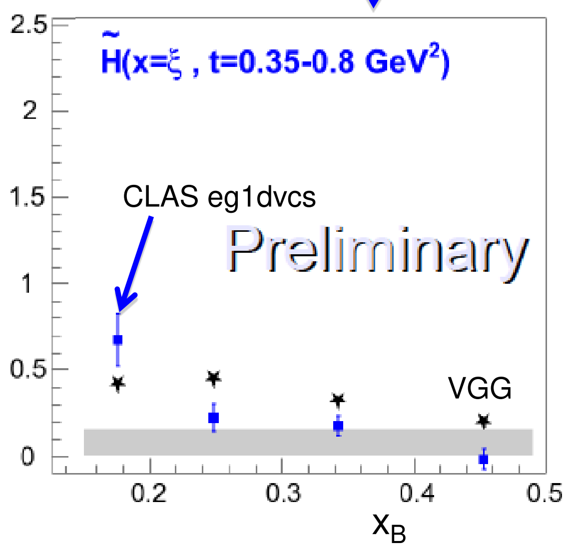


$\sigma_{UL}^{sin\phi} \sim F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)\mathcal{H}$

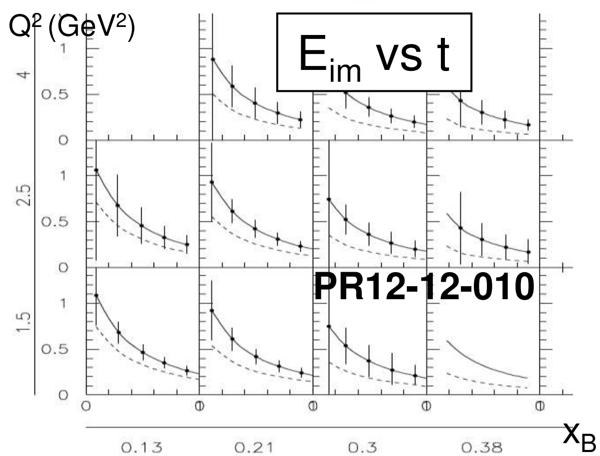


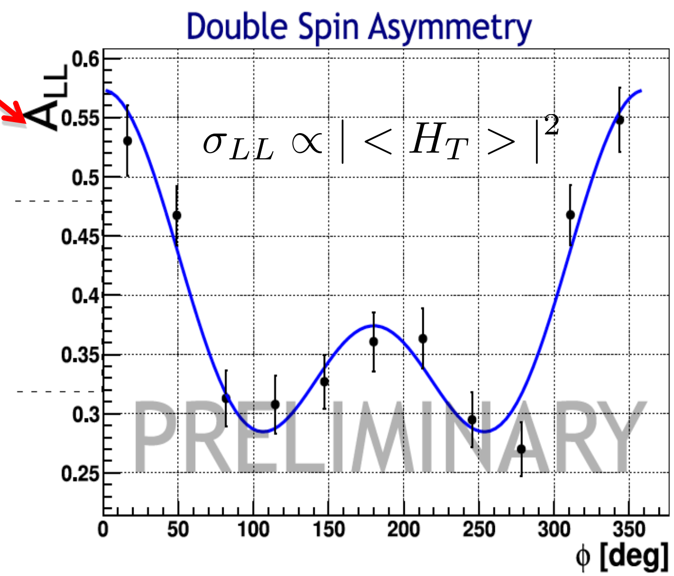
	ep→e' pγ		ep→e' pπ^0
	U	L	T
U	H		$\mathcal{E}_T$
L		$\tilde{H}$	
T	E		$H_T, \tilde{H}_T$





$\sigma_{UT}^{\cos\phi} \sim \frac{1-x}{2-x}\frac{t}{M^2}F_2\mathcal{H} + \frac{t}{4M^2}(2-x)F_1\mathcal{E}$





Spin-azimuthal asymmetries in hard exclusive photon (DVCS) and hadron (DVMP) production give access to underlying GPDs and PDFs

Summary

- **Measurements of azimuthal dependences of double and single spin asymmetries in hard scattering (SIDIS, DVMP) indicate that there are significant correlations between spin and transverse distribution of quarks**

- **Current JLab data are consistent with a partonic picture and measurements performed at higher energies**

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

Jlab measurements at 6 GeV provide important input for **model independent flavor decomposition** ***of TMDs and GPDs***

tools are required to extract the 3D PDFs in multidimensional space

Support slides….

The Multi-Hall SIDIS Program at 12 GeV

M. Aghasyan, K. Allada, H. Avakian, F. Benmokhtar, E. Cisbani, J-P. Chen, M. Contalbrigo, D. Dutta, R. Ent, D. Gaskell, H. Gao, K. Griffioen, K. Hafidi, J. Huang, X. Jiang, K. Joo, N. Kalantarians, Z-E. Meziani, M. Mirazita, H. Mkrtchyan, L.L. Pappalardo, A. Prokudin, A. Puckett, P. Rossi, X. Qian, Y. Qiang, B. Wojtsekhowski

for the Jlab SIDIS working group

The complete mapping of the multi-dimensional SIDIS phase space will allow a comprehensive study of the TMDs and the transition to the perturbative regime.

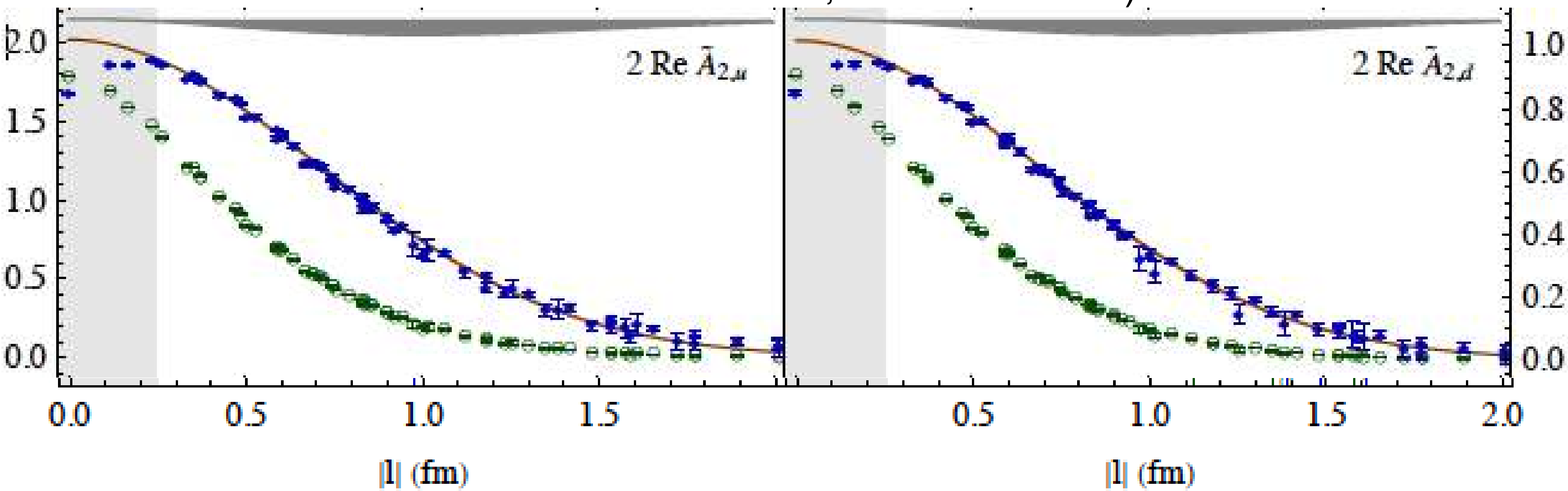
Flavor separation will be possible by the use of different target nucleons and the detection of final state hadrons.

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

Higher-twist effects will be present in both TMDs and fragmentation processes due to the still relatively low Q^2 range accessible at JLab, and can apart from contributing to leading-twist observables also lead to observable asymmetries vanishing at leading twist. These are worth studying in themselves and provide important information on quark-gluon correlations.

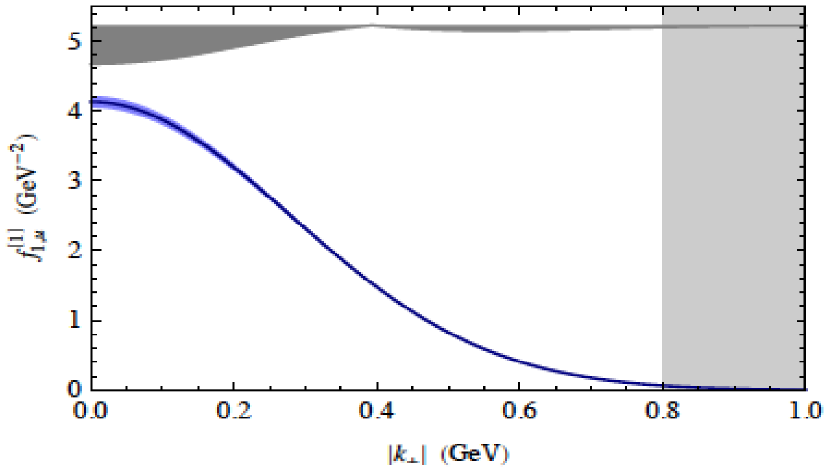
Lattice calculations and b_T-space

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

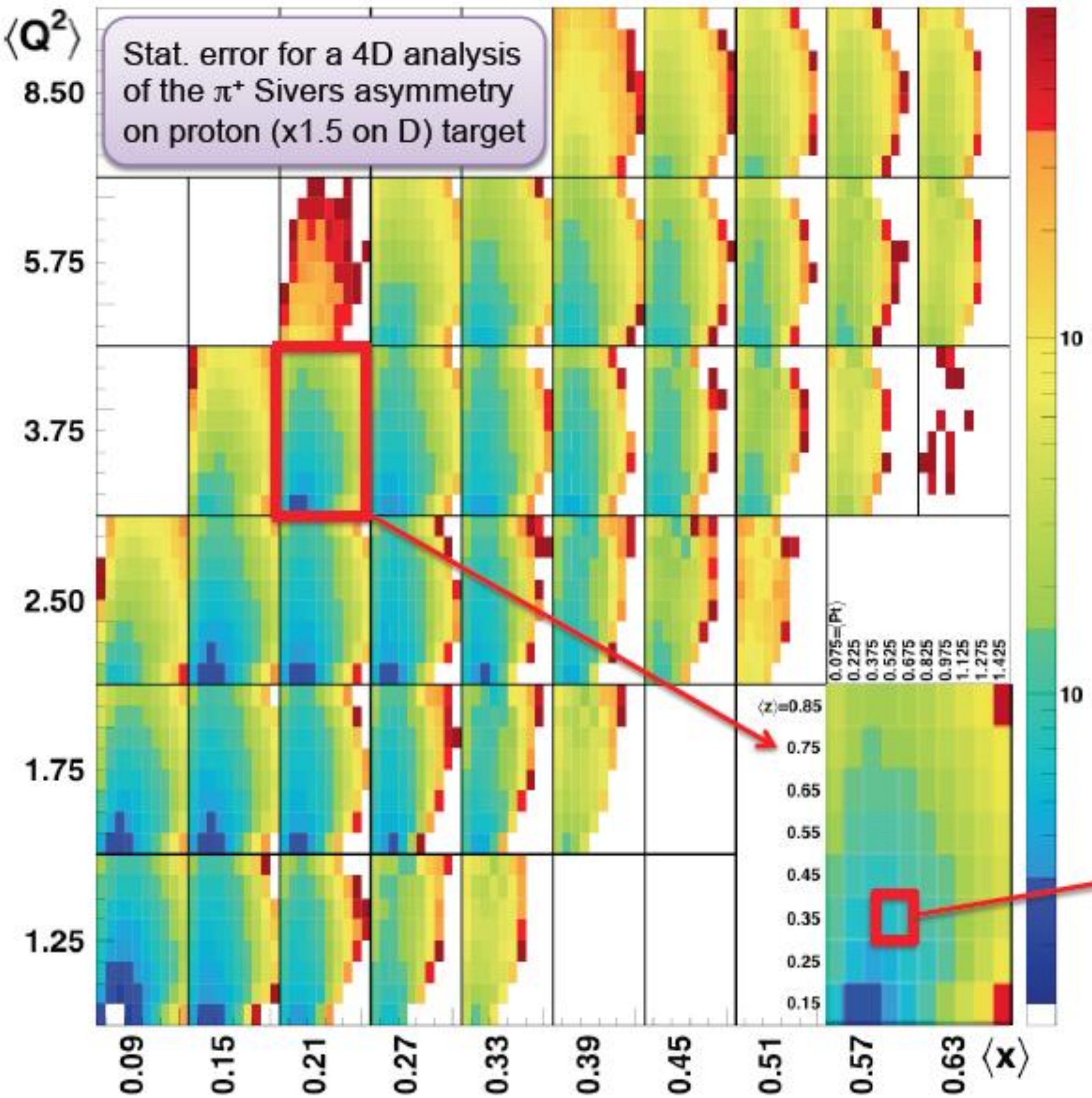


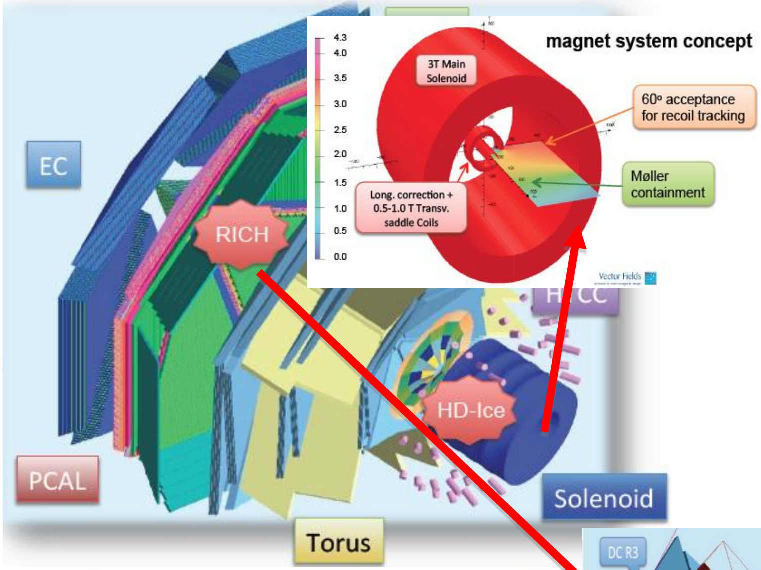
	c_2	σ_2
$\tilde{A}_{2,u}$	$2.0186 \pm 0.0063 \pm 0.0008$	$1.001 \pm 0.010 \pm 0.068$
$\tilde{A}_{2,d}$	$1.0171 \pm 0.0064 \pm 0.0005$	$0.975 \pm 0.012 \pm 0.063$

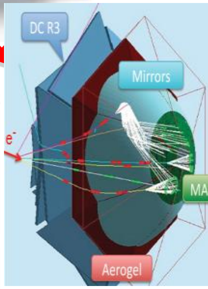
$$f_1^{[1]}(\boldsymbol{k}_\perp^2) = \frac{c_2\,\sigma_2^2}{4\pi} e^{-\frac{\boldsymbol{k}_\perp^2}{(2/\sigma_2)^2}}$$

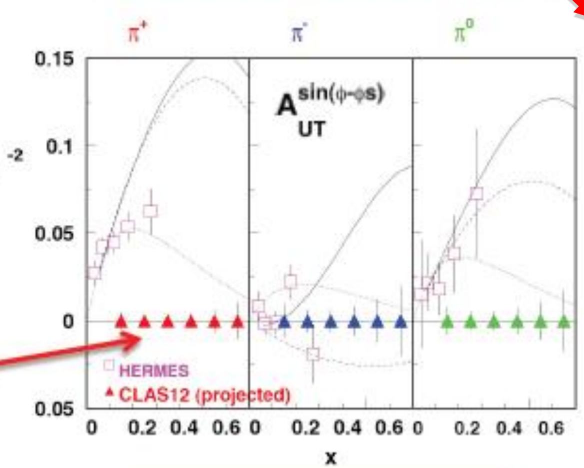


CLAS12 A_{UT} with transverse proton target

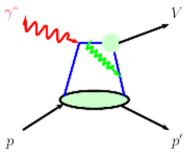








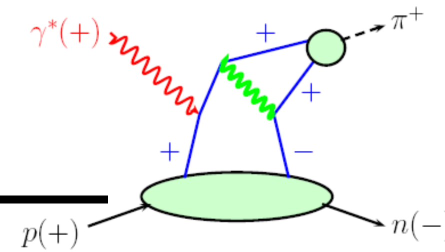
Curves from hep-ph/0507266 and hep-ph/0507181



SSAs in exclusive pion production

Transverse photon matters

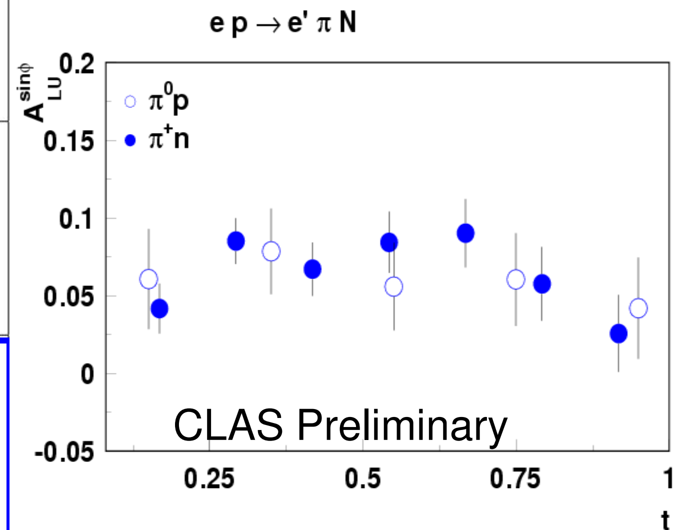
Ahmad,Liuti & Goldstein: arXiv:0805.3568
Gloskokov & Kroll : arXiv:0906.0460

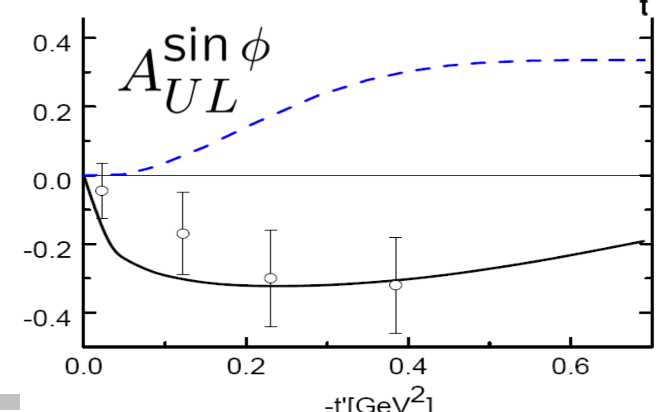


$$\mathcal{M}^{twist-3}_{0-,++} \approx e_0\sqrt{1-\xi^2}\int_{-1}^{+1} d\bar{x}\mathcal{H}_{0-,++}[H_T^{(3)}+\ldots]$$

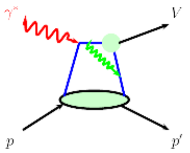
observable	dominant interf. term	amplitudes	low t' behavior
$A_{UT}^{\sin(\phi-\phi_s)}$	LL	$\mathrm{Im}[\mathcal{M}^*_{0-,0+}\mathcal{M}_{0+,0+}]$	$\propto \sqrt{-t'}$
$A_{UT}^{\sin(\phi+\phi_s)}$	TT	$\mathrm{Im}[\mathcal{M}^*_{0-,++}\mathcal{M}_{0+,++}]$	$\propto \sqrt{-t'}$
$A_{UT}^{\sin(3\phi-\phi_s)}$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

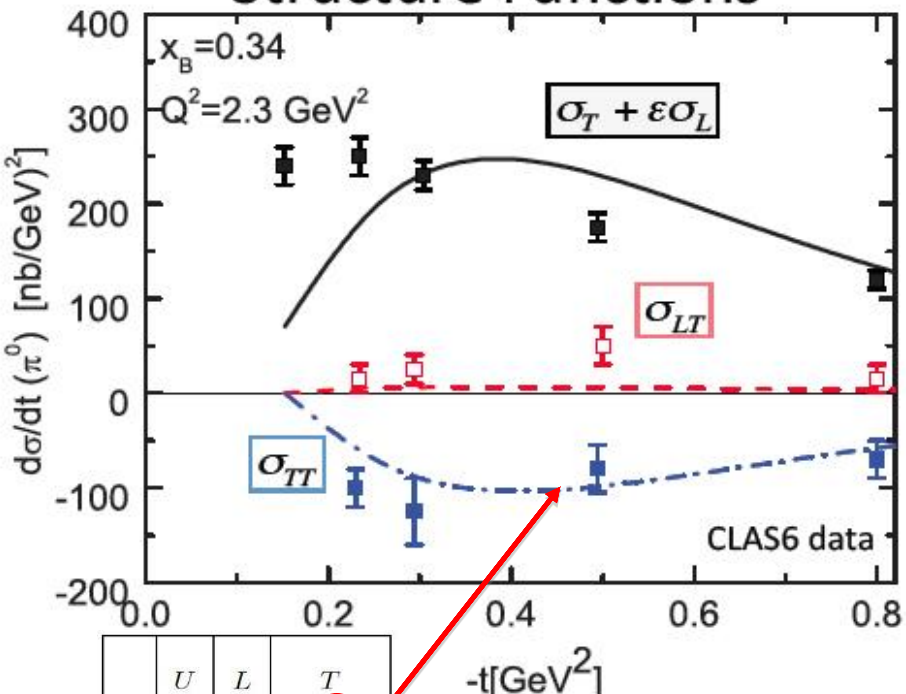


Exclusive π^0 production

Recent progress with GPD-based description

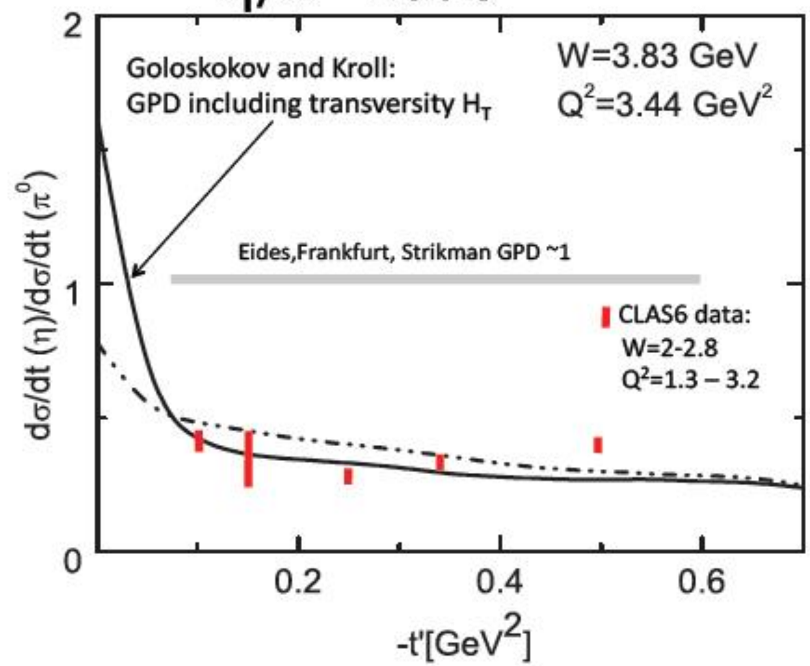
- Goloskokov&Kroll , Goldstein&Liuti . Include ***transversity*** **GPDs** H_T and $\mathcal{E}_T = 2\tilde{H}_T + E_T$ Dominate in CLAS kinematics. Successfully described data.

Structure Functions



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

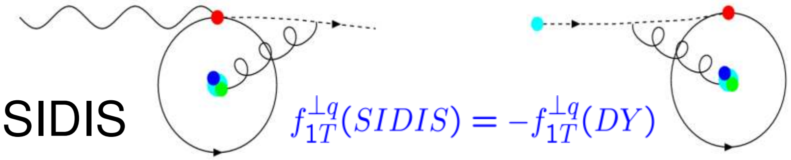
η/π^0 Ratio



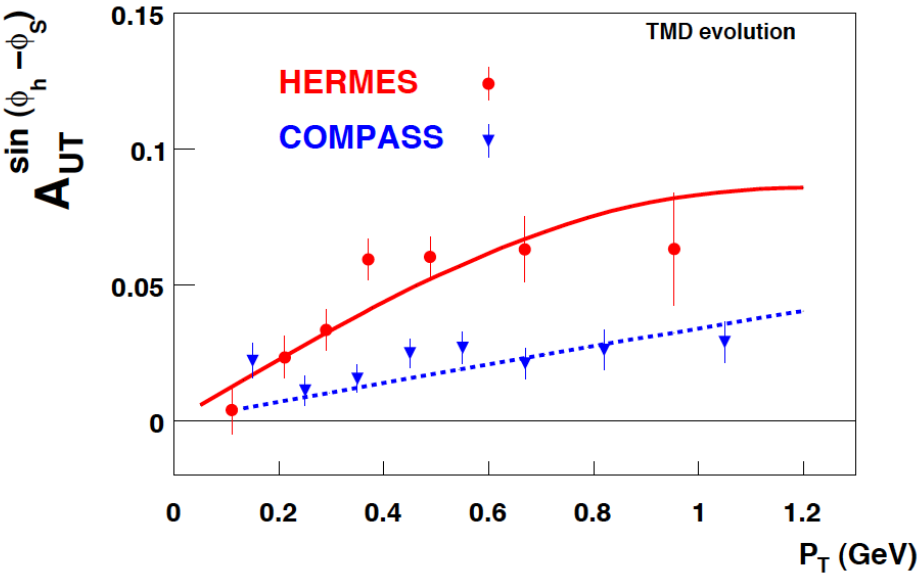
Goloskokov&Kroll
H_T and $\bar{E}_T$ dominate

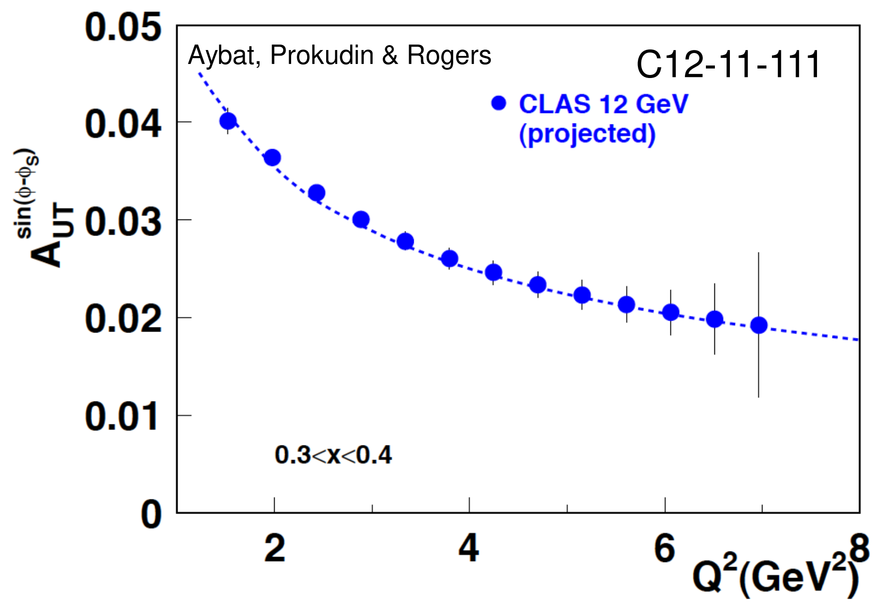
Sivers TMD evolution

SIDIS



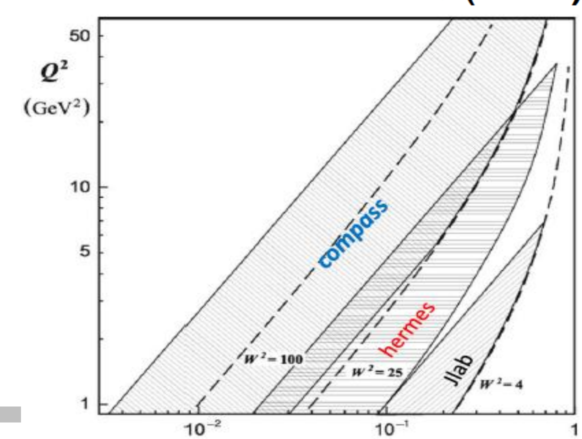
Drell-Yan



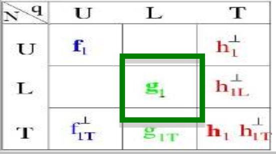


TMD Evolution may explain existing differences between HERMES and COMPASS .

Aybat, Prokudin & Rogers : arXiv:1112.4423



Comparison of JLab12 data with HERMES and COMPASS will pin down the Q^2 evolution of Sivers asymmetry.

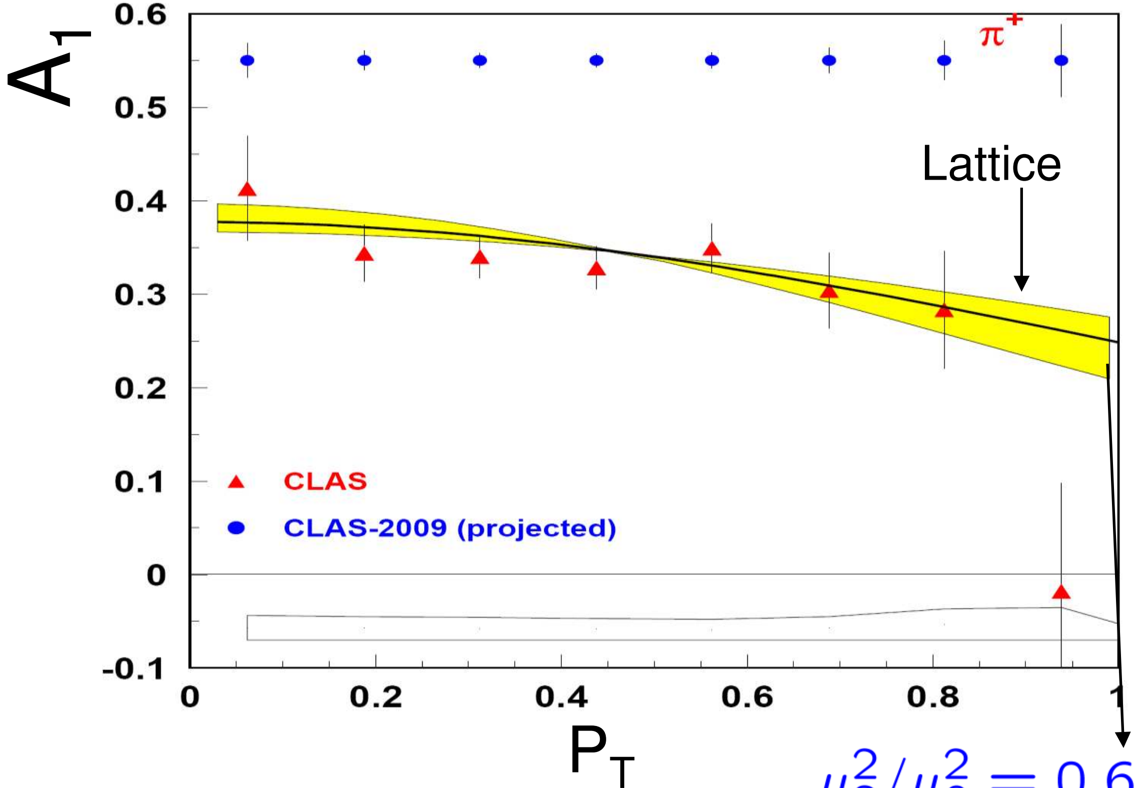


A_1 P_T-dependence

arXiv:1003.4549

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

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

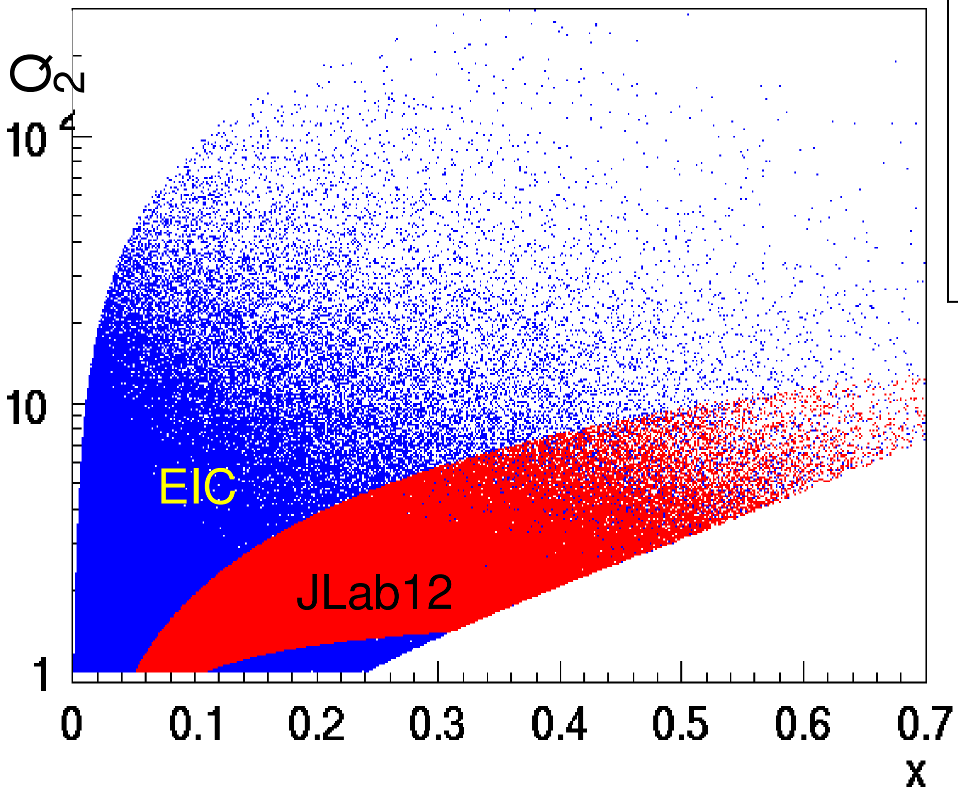


B.Musch et al arXiv:1011.1213

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

CLAS data consistent with model predictions and lattice predicting that width of g_1 is less than the width of f_1

From JLab12 to EIC

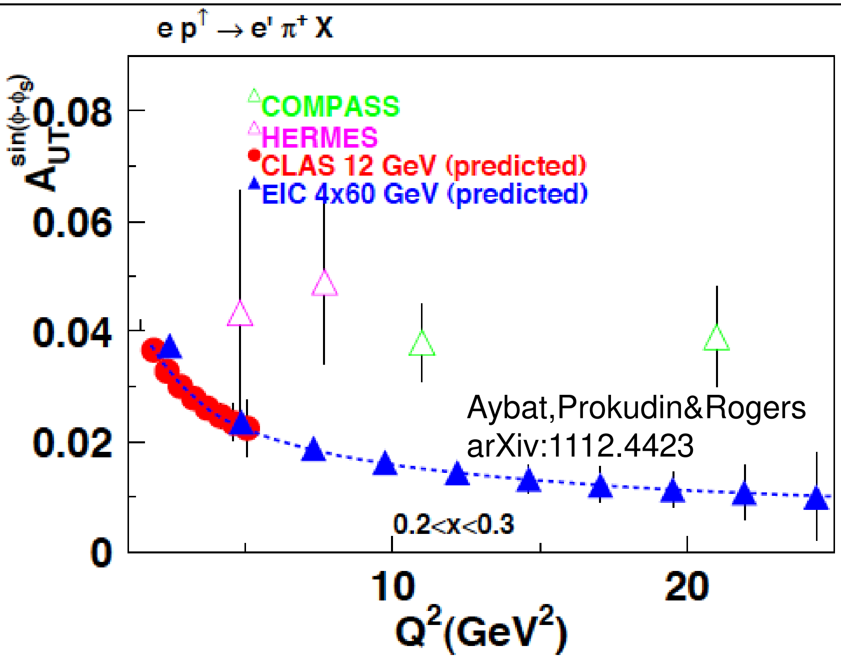


JLab@12GeV (25/50/75)

→0.1<x_B<0.7 : valence quarks

EIC √s = 140, 50, 15 GeV

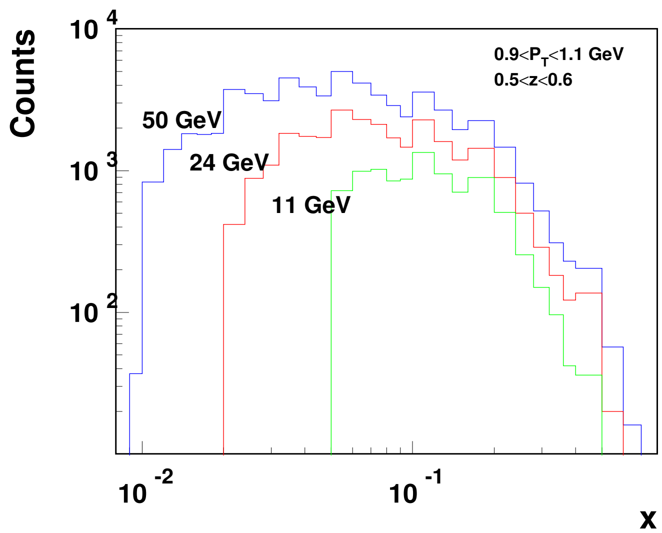
→10^{-4}<x_B<0.3: gluons and quarks, higher P_T and Q^2.

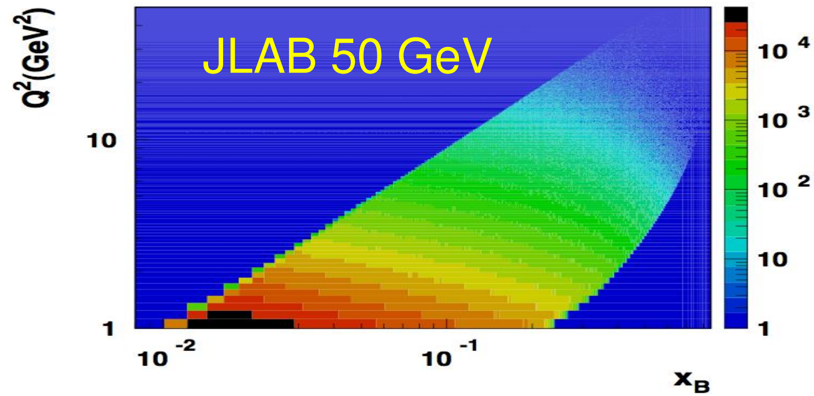


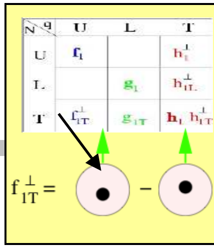
$$A_{UT}^{\sin(\phi-\phi_S)} = \frac{\sum_q e_q^2 f_{1T}^{\perp q} D_1^q}{\sum_q e_q^2 f_1^q D_1^q}$$

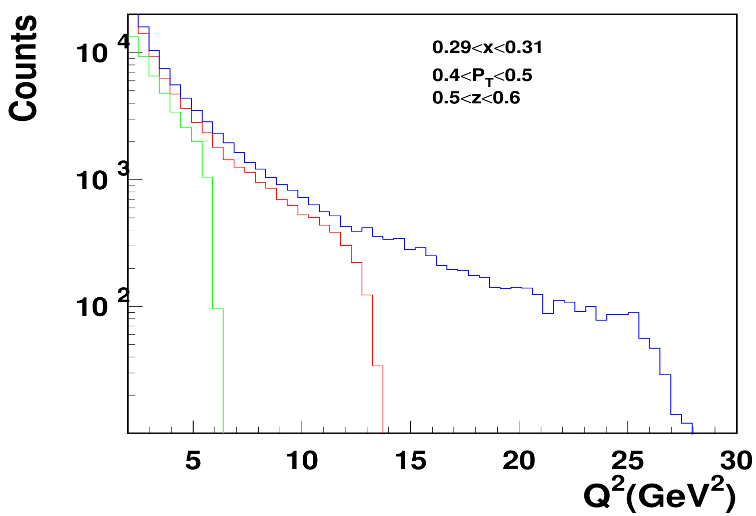
- Study of high **x** domain requires high luminosity, low **x** higher energies
- Wide range in Q^2 is crucial to study the evolution
- Overlap of EIC and JLab12 in the valence region will be crucial for the TMD program

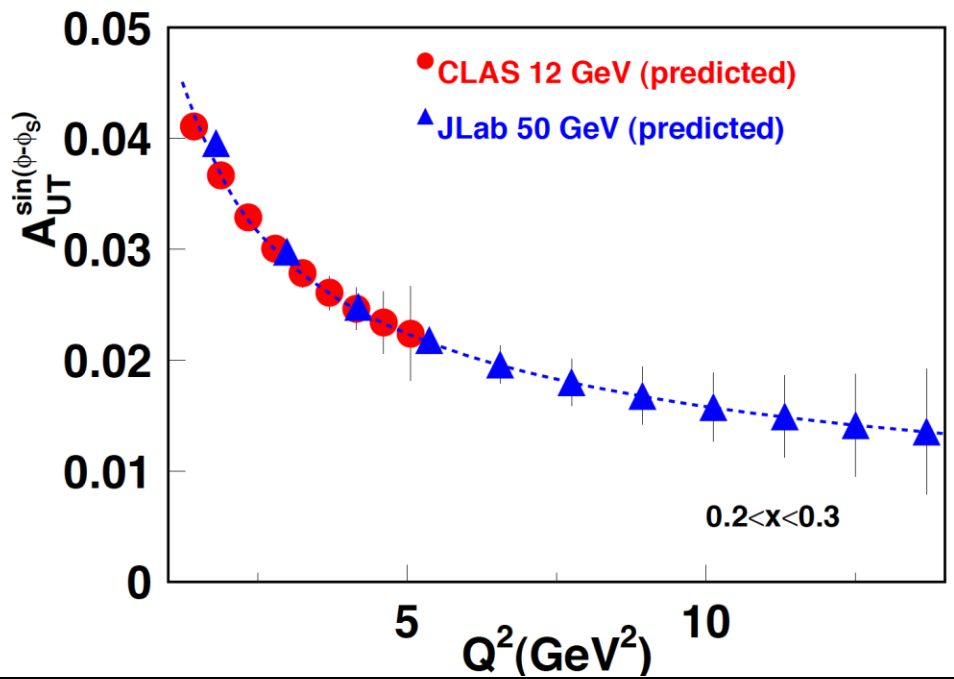
$ep \rightarrow e' \pi^+ X$ From JLab12 to JLab50





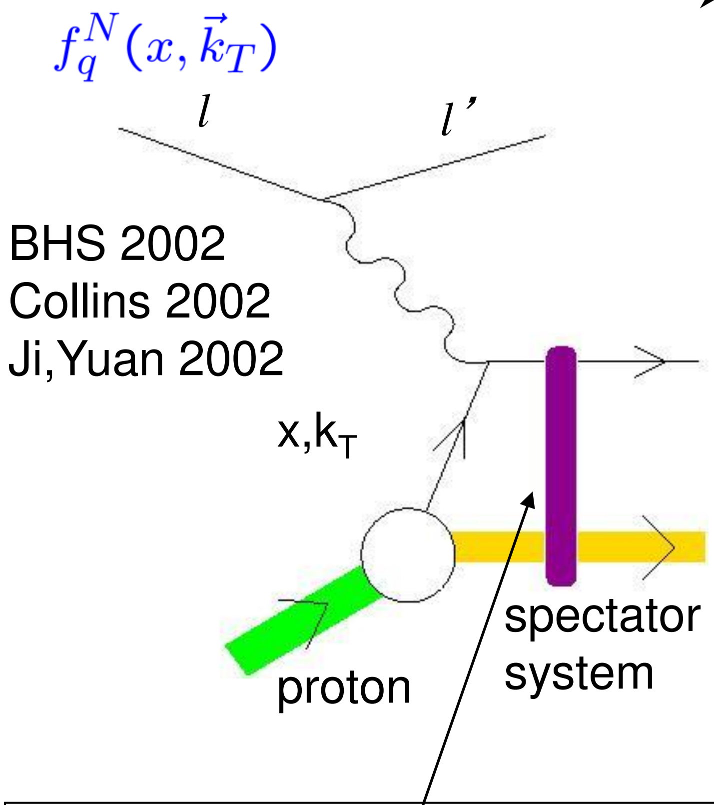






For a given lumi (30min of runtime) and given bin in hadron z and P_T, higher energy provides higher counts and wider coverage in Q^2, allowing studies of Q^2 evolution of 3D partonic distributions in a wide Q^2 range.

k_T and FSI



soft gluon exchanges included in the distribution function (gauge link)

- Factorization proven for small k_T (Ji,Ma,Yuan 2005)
- Medium modifications of k_T PDFs (Tang, Wang, Zhou 2008)
- 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)
- Color Lorentz Force acting on ejected quark, torque along trajectory (Burkardt 2008, 2012)
- k_T-dependent flavor decomposition (BGMP procedure,2011)

•Experiments consistent with evolution on $\langle k_T^2 \rangle$ increasing with Q^2.
•What is the source of the k_T (dynamical vs static)?
•What is the role of FSI and how they modify in medium

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

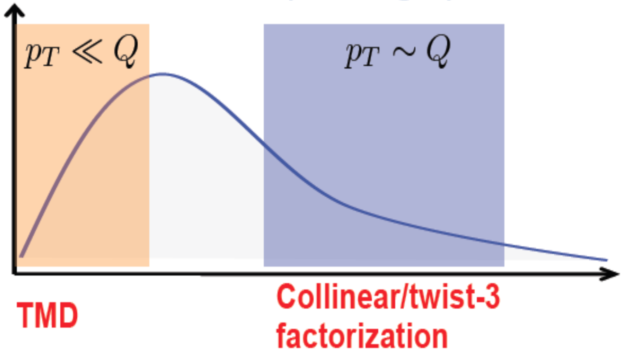
$\frac{M^2}{2} e_2$ Boer-Mulders Force on the active quark right after scattering (t=0)

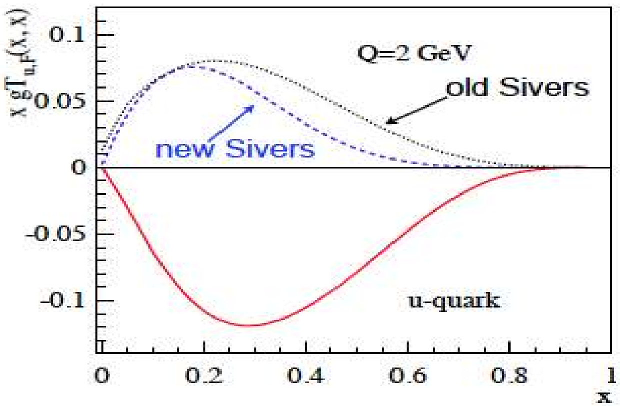
Interpreting HT (quark-gluon-quark correlations) as force on the quarks (Burkardt hep-ph:0810.3589)

current quark masses

k_T-dependence of TMDs

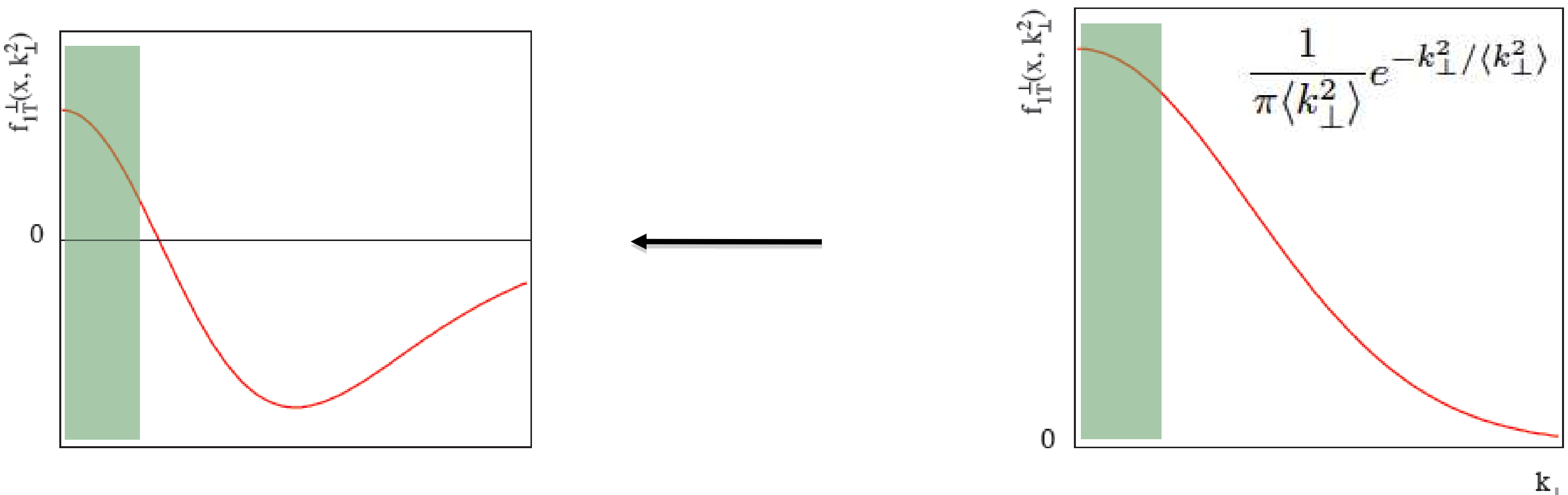
- Transition from low p_T to high p_T





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



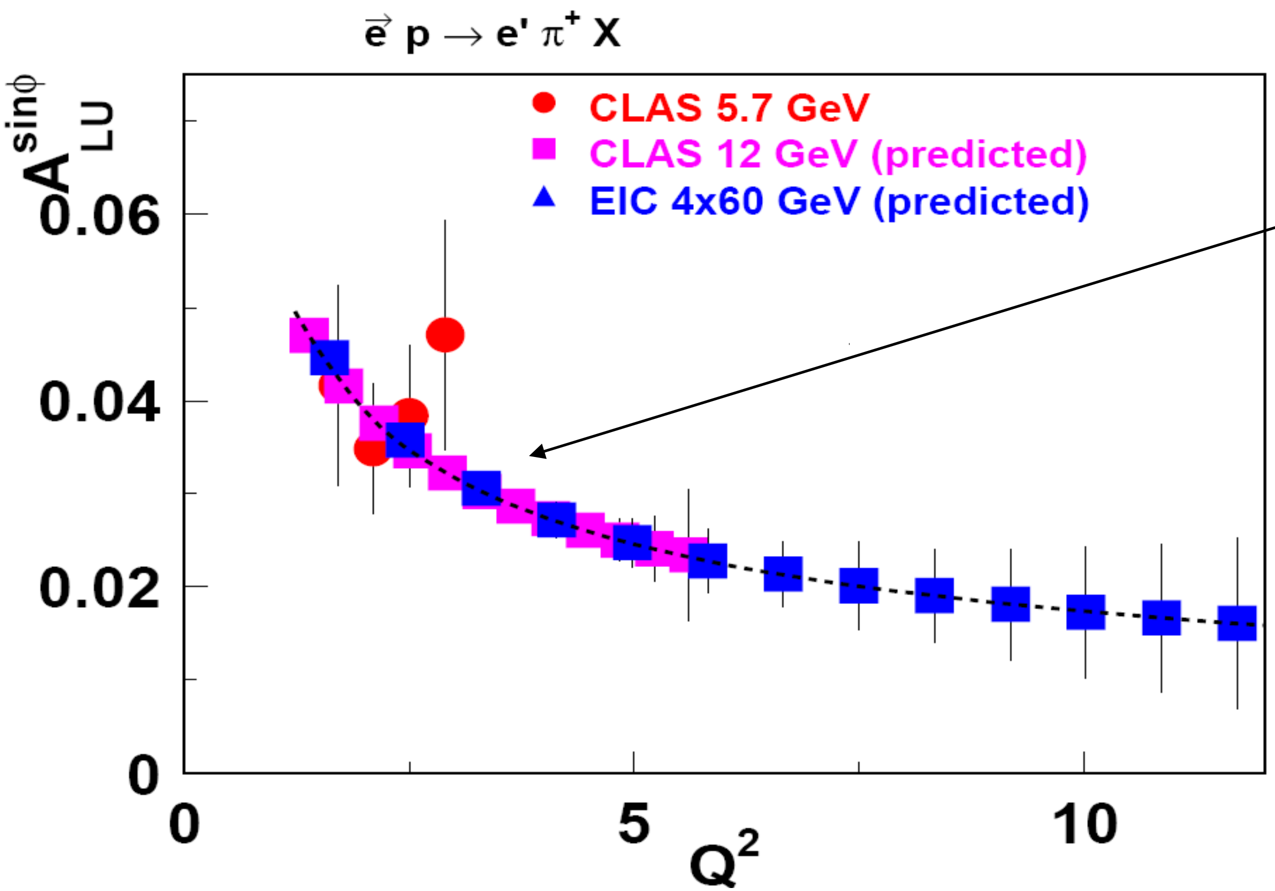
- With orbital angular momentum TMD can't be gaussian
- How to measure k_T-dependences of TMDs

(Z. Kang et al, 2011)

Q^2-dependence of beam SSA

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

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



1/Q behavior expected (fixed x bin)

Study for Q^2 dependence of beam SSA allows to check the higher twist nature and access quark-gluon correlations.

P_T-dependence studies at Hall-C

H. Mkrtchyan(DIS2011)

Experiment E00-108

Beam energy 5.5 GeV

4 cm LH2 and LD2 targets

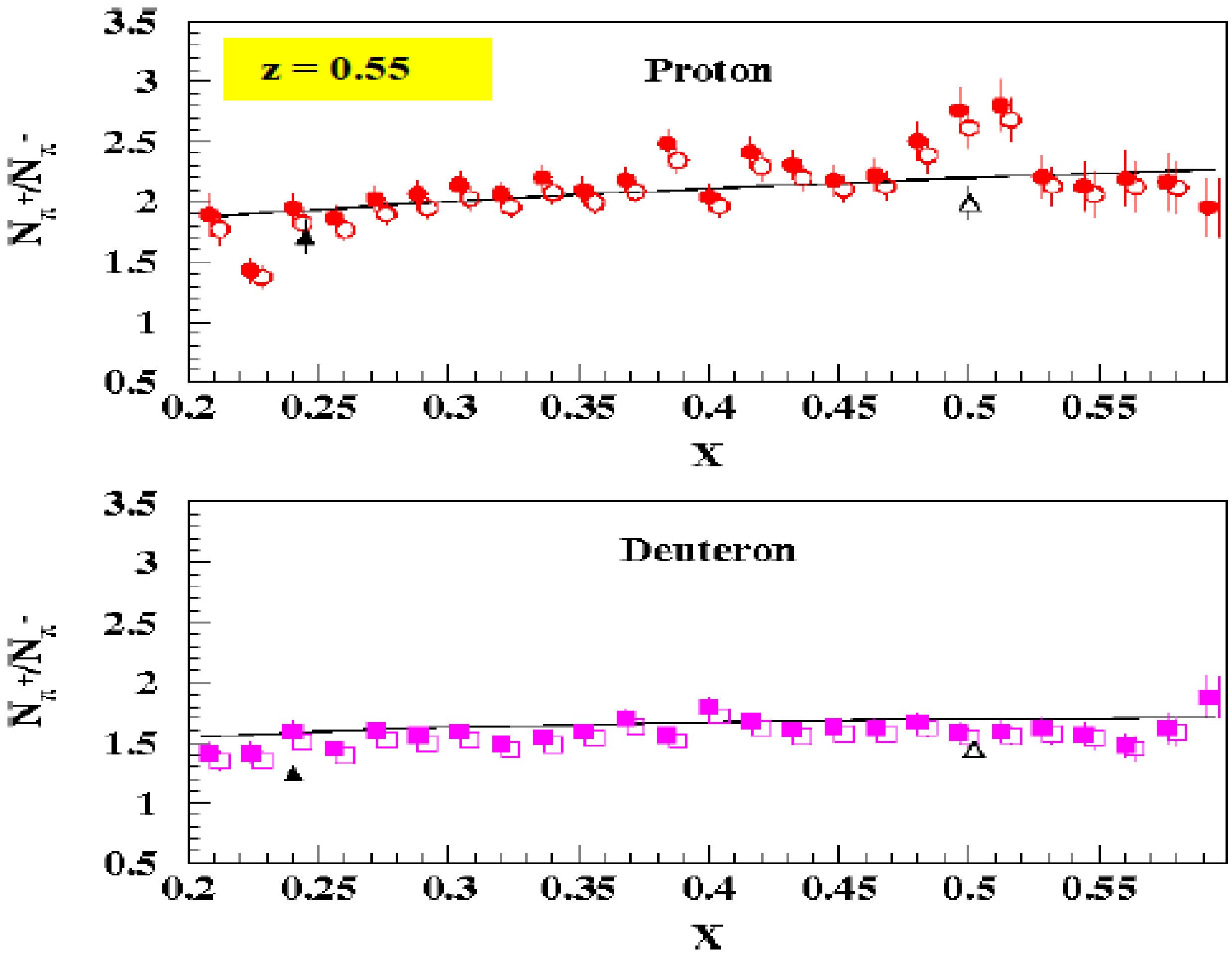
$$\sigma_d^{\pi^+} \propto (4D^+ + D^-)(u+d)$$

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

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

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

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

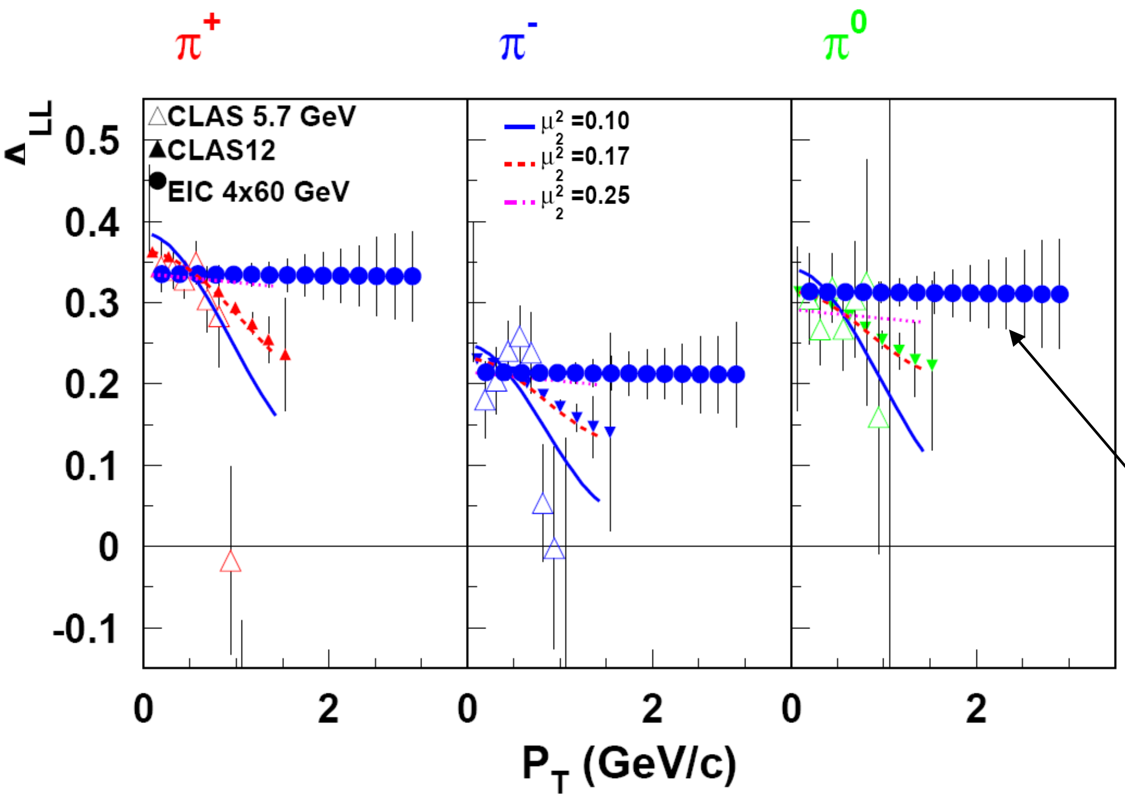


x-dependence of π+/π- ratio is good agreement with the quark parton model predictions (lines CTEQ5M+BKK).

A_1 P_T-dependence in SIDIS

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

M.Anselmino et al
hep-ph/0608048



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

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

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

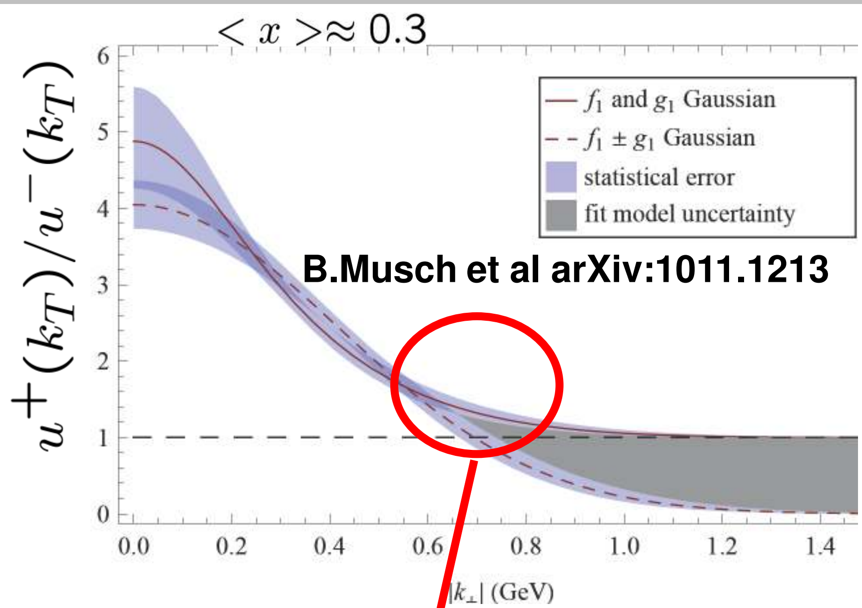
$\mu_0^2=0.25\text{GeV}^2$
$\mu_D^2=0.2\text{GeV}^2$

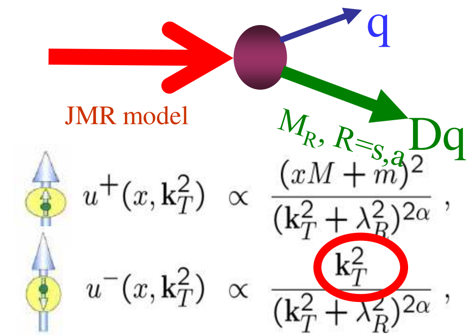
Perturbative limit calculations available for $g_1^q(x,k_T), f_1(x,k_T)$:

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**

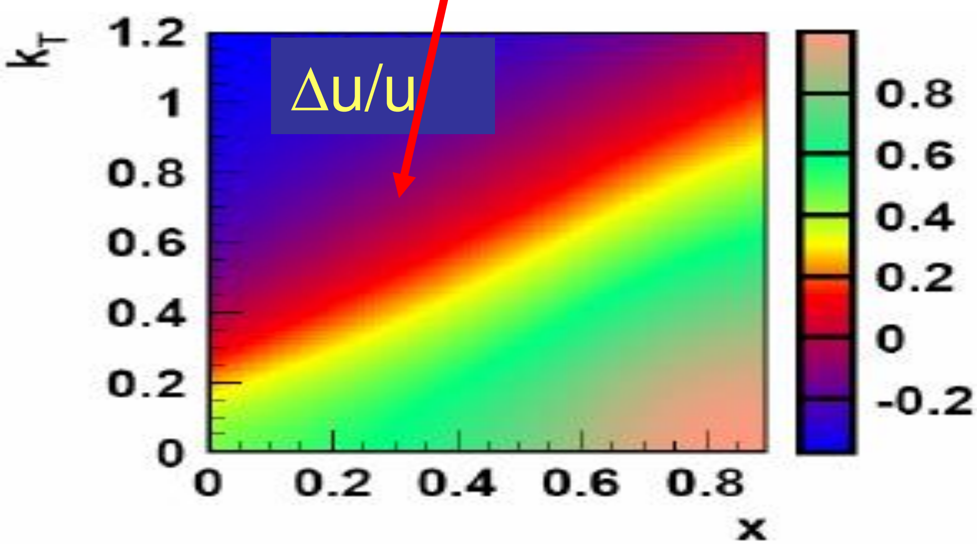
Quark distributions at large k_T: models





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

$$u^-(x, k_T^2) \propto \frac{k_T^2}{(k_T^2+\lambda_R^2)^{2\alpha}},$$



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

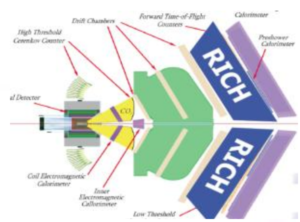
E12-07-107: Studies of Spin-Orbit Correlations with Longitudinally Polarized Target

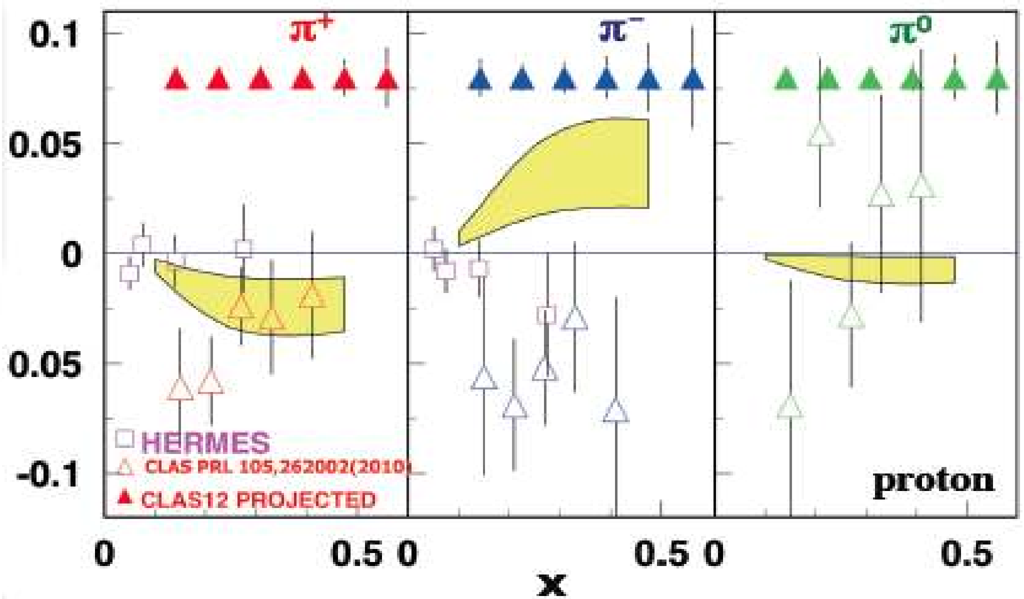
N \ q	U	L	T
L		g_{1L}	$h_{1L}^{\perp}$

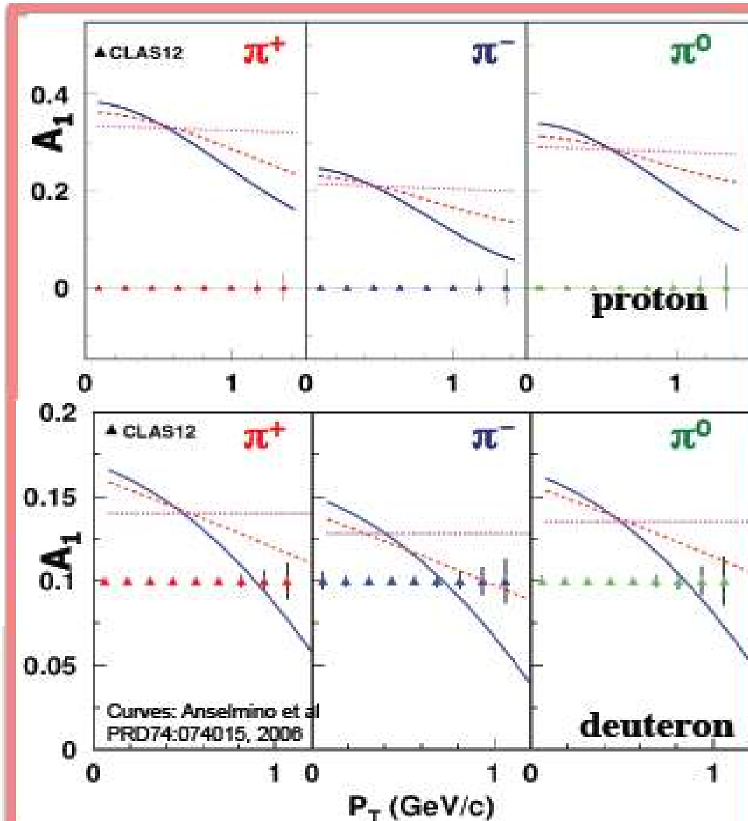
$$\frac{d\sigma}{dx\,dy\,d\phi_S\,d\phi_h\,dP_{h\perp}^2} \propto S_L\left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi_h F_{UL}^{\sin\phi_h} + \epsilon\sin(2\phi_h) F_{UL}^{\sin(2\phi_h)}\right]$$

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

h.t. ($F_{UL}^{\sin\phi_h}$); $h_{1L}^{\perp}\otimes H_1^{\perp}$ ($F_{UL}^{\sin(2\phi_h)}$); $g_{1L}\otimes D_1$ (F_{LL}); h.t. ($F_{LL}^{\cos(\phi_h)}$)





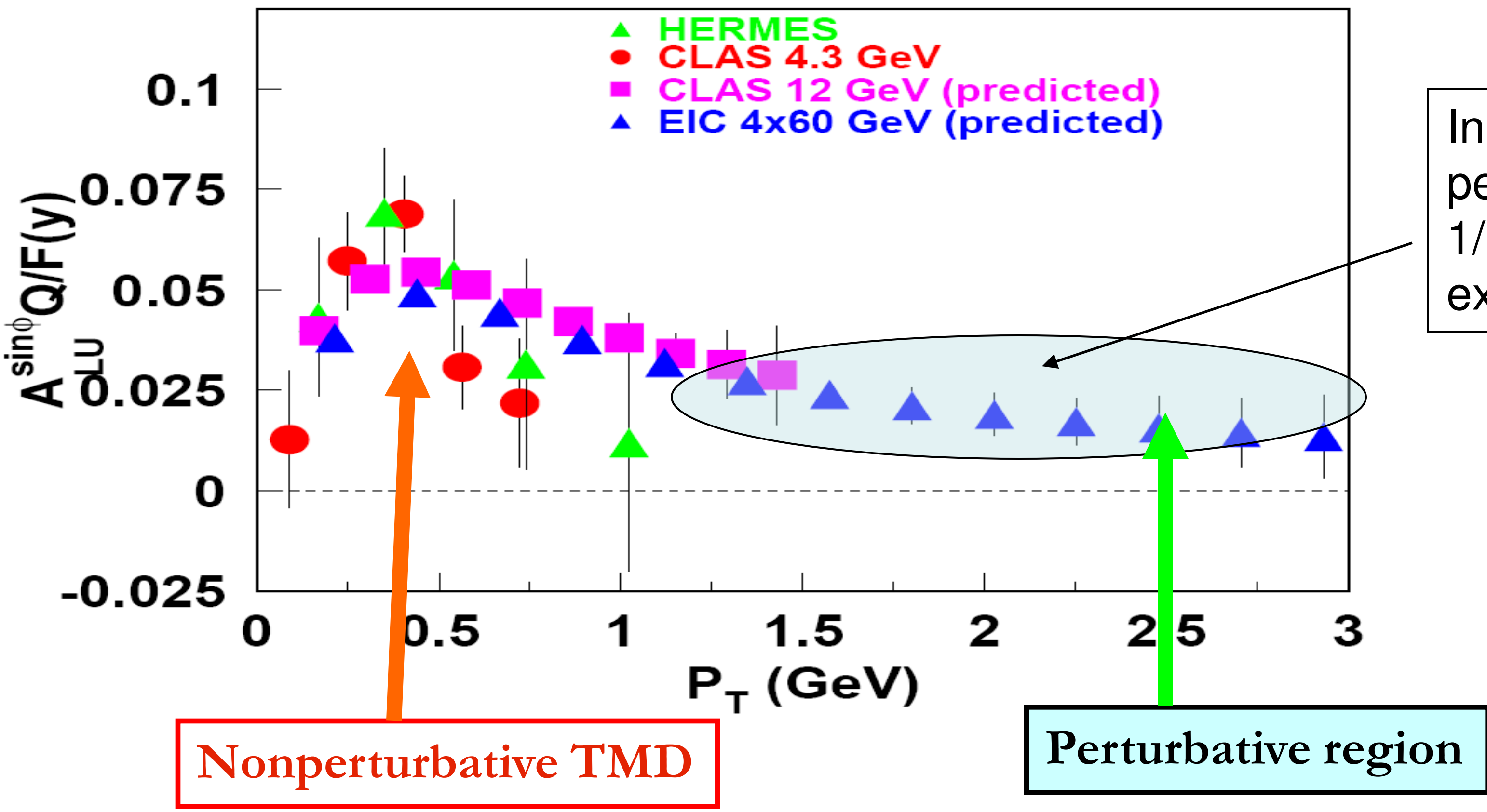


- A_1 P_T-dependence provides access to helicity dependence of k_T-distributions of quarks
- p & d data required for P_T-dependence flavor decomposition

P_T-dependence of beam SSA

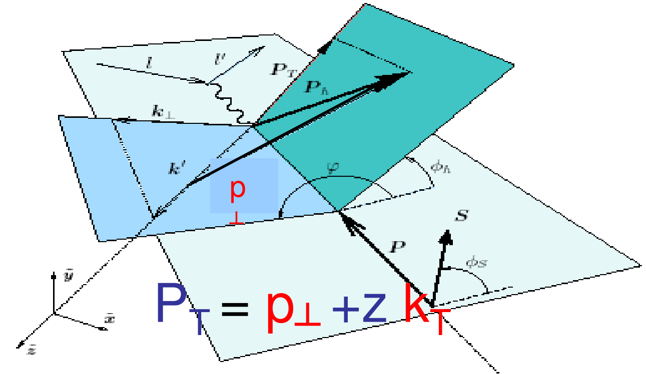
$\sigma^{\sin\phi}_{LU(UL)} \sim F_{LU(UL)} \sim 1/Q$ (Twist-3)

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



Study for SSA transition from non-perturbative to perturbative regime.
EIC will significantly increase the P_T range.

FAST-MC for CLAS12



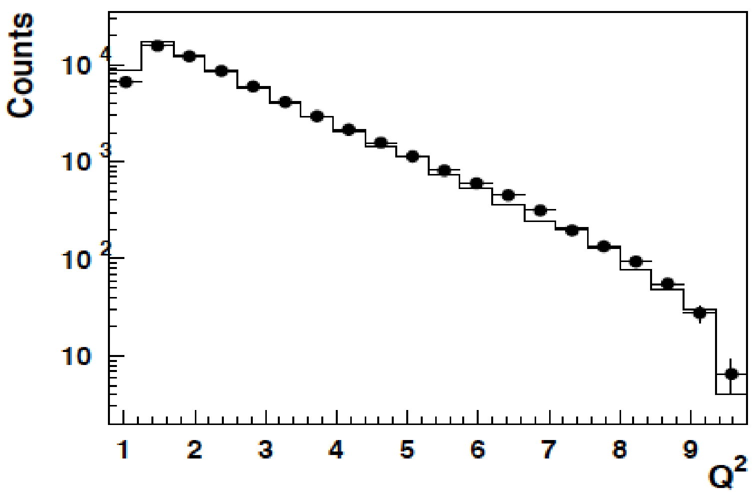
SIDIS MC in 8D $(x,y,z,\phi,\phi_S,p_T,\lambda,\pi)$

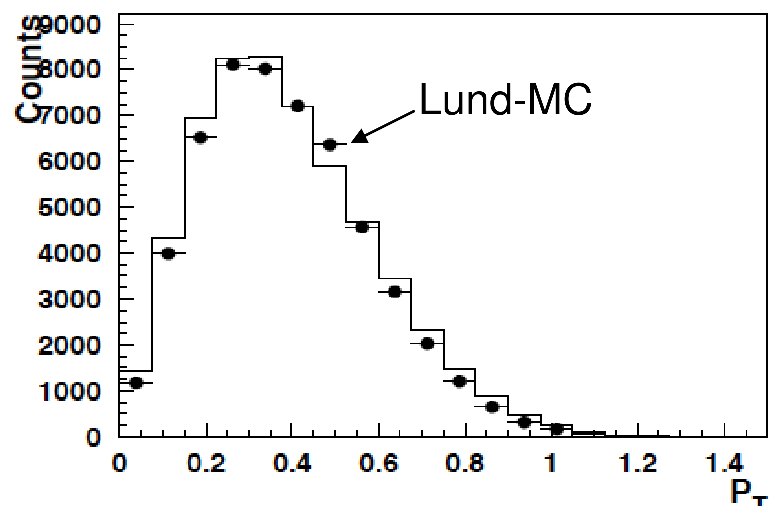
Simple model with 10% difference between f1 (0.2GeV^2) and g1 widths with a fixed width for D1 (0.14GeV^2)

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

CLAS12 acceptance & resolutions

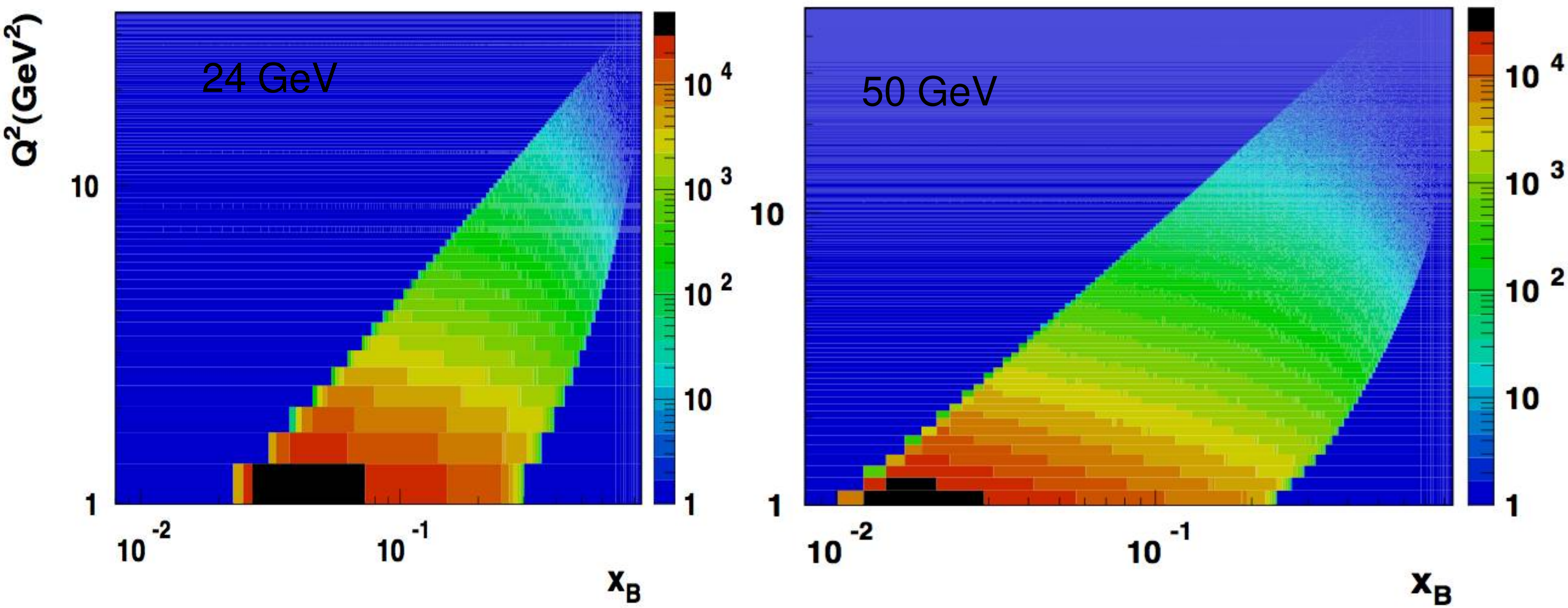
Events in CLAS12



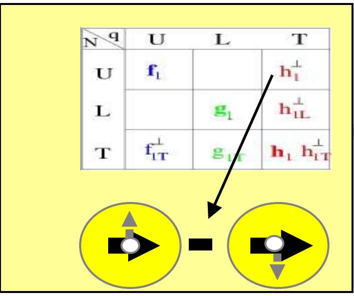


Reasonable agreement of kinematic distributions with realistic LUND simulation

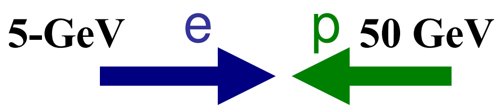
$ep \to e' \pi^+ X$ Kinematic coverage



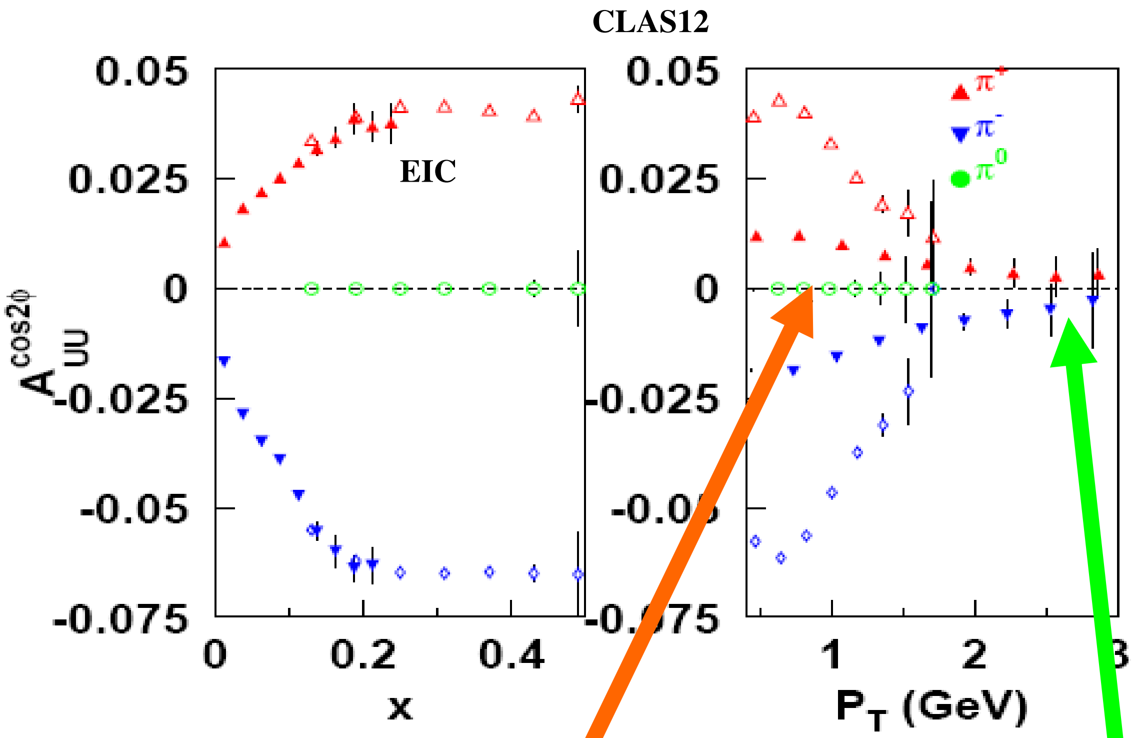
For a given lumi (30min of runtime with $L=10^{35} cm^{-2}s^{-1}$) and given bin in hadron z and P_T, higher energy provides higher counts and wider coverage in x and Q^2



Boer-Mulders Asymmetry with CLAS12 & EIC



Transversely polarized quarks in the unpolarized nucleon



sin(ϕ_C) =cos(2ϕ_h)

$$A_{UU}^{\cos 2\phi} \propto h_1^{\perp(1)} H_1^{\perp}$$

$$\langle \cos 2\phi \rangle|_{P_{h\perp} \gg \Lambda_{QCD}} \propto \frac{1}{P_{h\perp}^2}$$

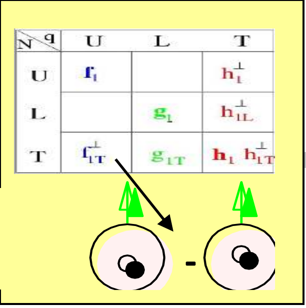
Nonperturbative TMD

Perturbative region

Perturbative limit calculations available for $f_1(x, k_T), h_1^\perp(x, k_T)$

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

CLAS12 and ELIC **studies of transition from non-perturbative to perturbative regime will provide complementary info on spin-orbit correlations and test unified theory (Ji et al)**

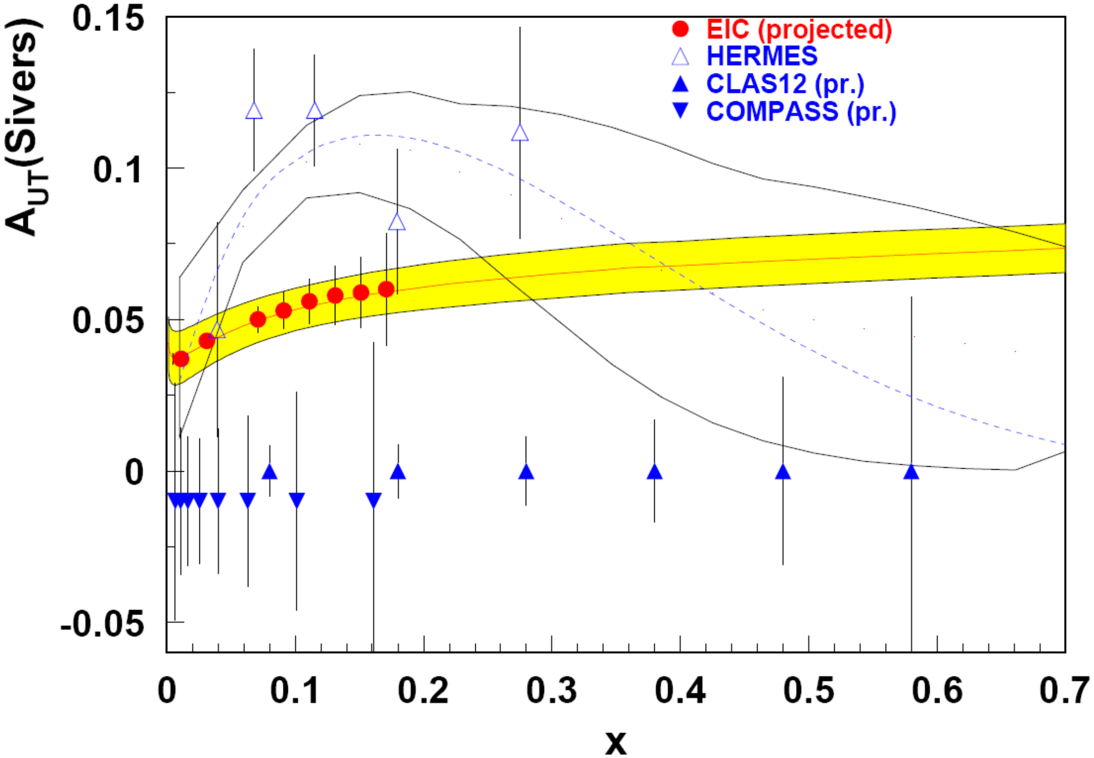


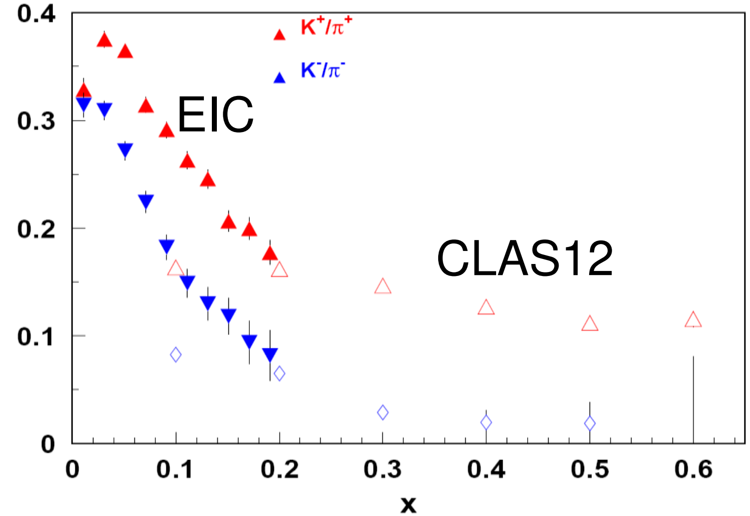
Sivers effect: Kaon electroproduction

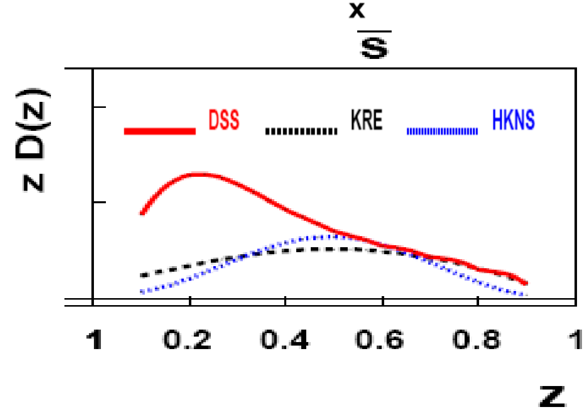
$$A_{UT}^{\sin(\phi-\phi_S)} = \frac{\sum_q e_q^2 f_{1T}^{\perp q} D_1^q}{\sum_q e_q^2 f_1^q D_1^q}$$

$K^+ \sim u\bar{s}$ $\qquad$ $K^- \sim s\bar{u}$

ep→e' K$^+$+X







- At small x of EIC Kaon relative rates higher, making it ideal place to study the Sivers asymmetry in Kaon production (in particular K-).
- Combination with CLAS12 data will provide almost complete x-range.

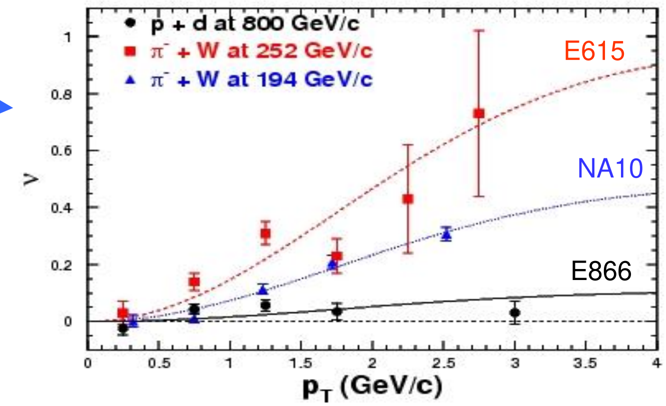
TMD Correlation Functions in other experiments

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



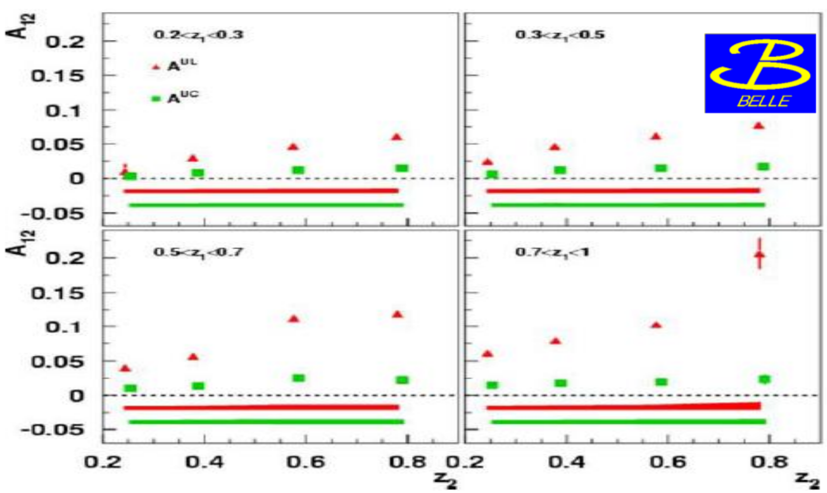
Fragmentation Functions (FF)

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

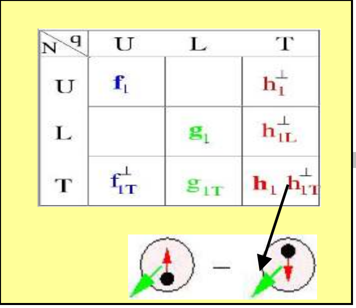
COLLINS
Quark spin probe

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

ee → ππX

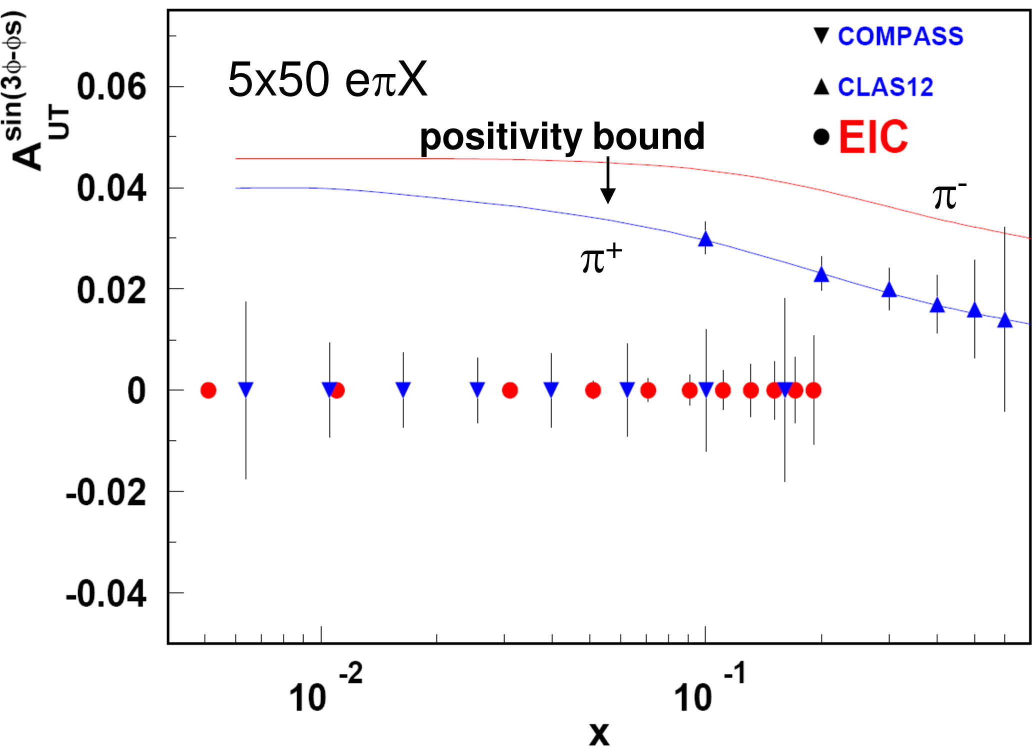


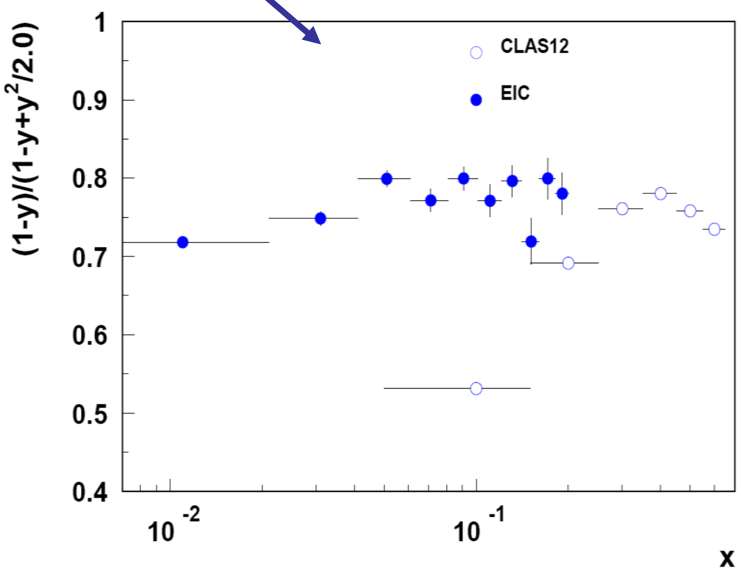
In di-hadron case $H_1^{\sphericalangle}$ Interference Fragmentation Function (IFF)



Pretzelosity @ EIC

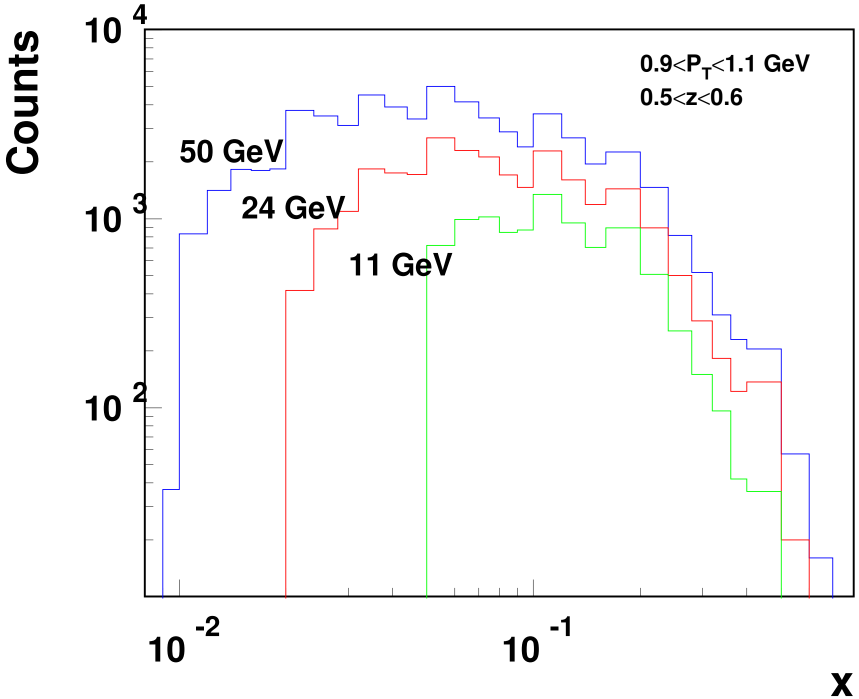
$$A_{UT}^{\sin(3\phi-\phi_S)} \propto \frac{1-y}{1-y+y^2/2} \frac{\sum_q e_q^2 h_{1T}^{\perp(1)q} H_1^{\perp q}}{\sum_q e_q^2 f_1^q D_1^q}$$



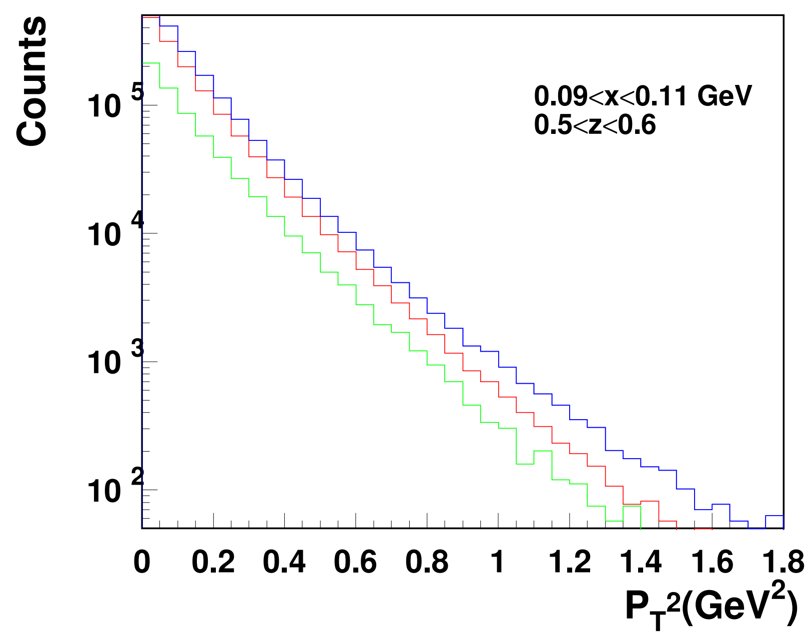


•EIC measurement combined with CLAS12 will provide a complete kinematic range for pretzelosity measurements

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



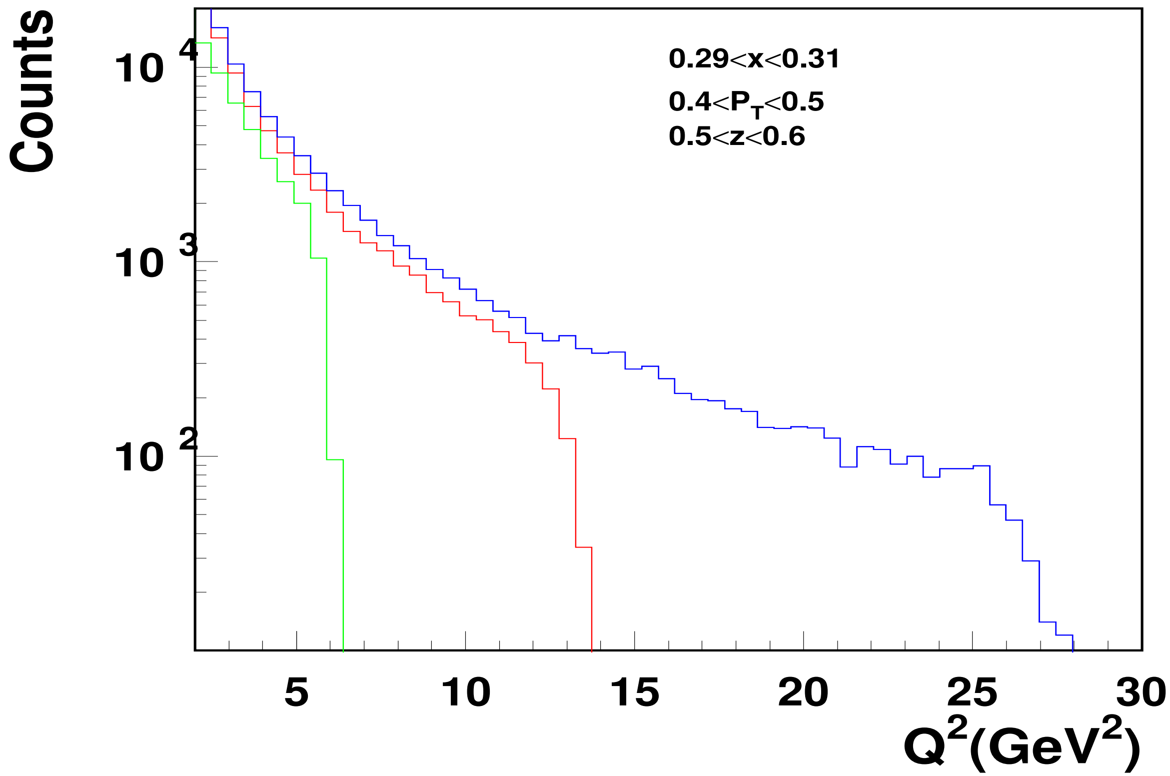
Wider x range allow studies of transverse distributions of sea quarks and gluons



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

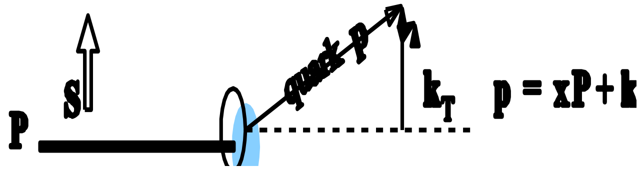
For a given lumi (30min of runtime with 10^{35}) and given bin in hadron z and P_T, higher energy provides higher counts and wider coverage in x and P_T to allow studies of correlations between longitudinal and transverse degrees of freedom

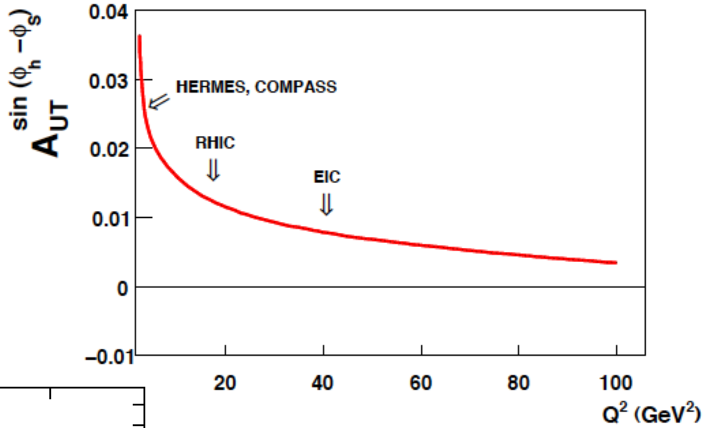
$ep \rightarrow e' \pi^+ X$ Kinematic coverage

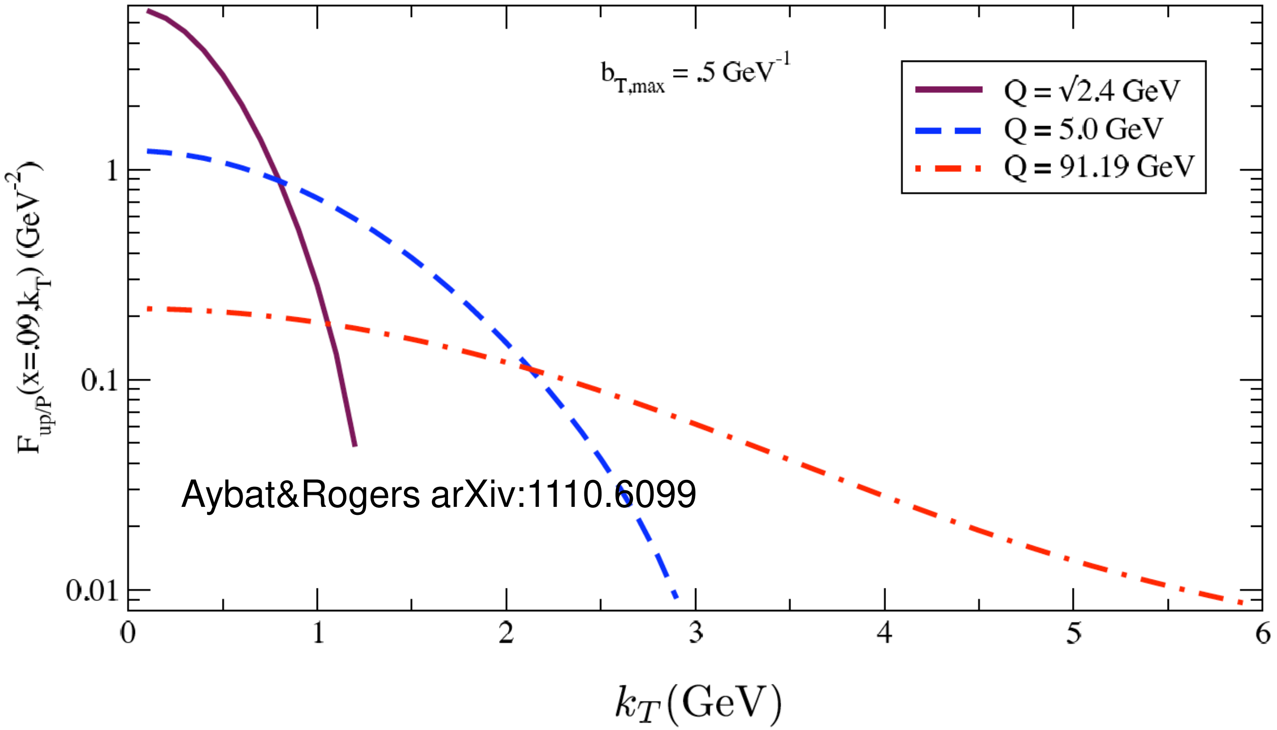


For a given lumi (30min of runtime) and given bin in hadron z and P_T, higher energy provides higher counts and wider coverage in Q^2, allowing studies of Q^2 evolution of 3D partonic distributions in a wide Q^2 range.

Evolving TMD PDFs



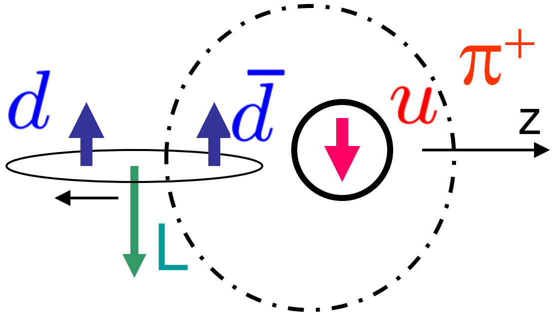




Aybat&Rogers arXiv:1110.6099

Collins effect

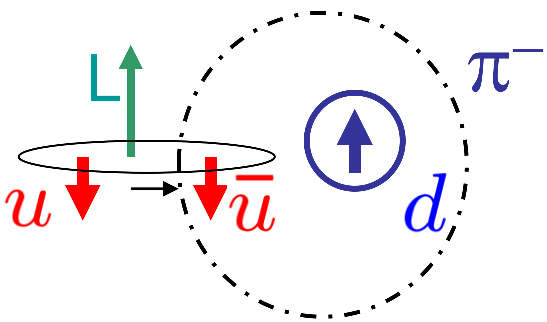
Simple string fragmentation (Artru model)



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)

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

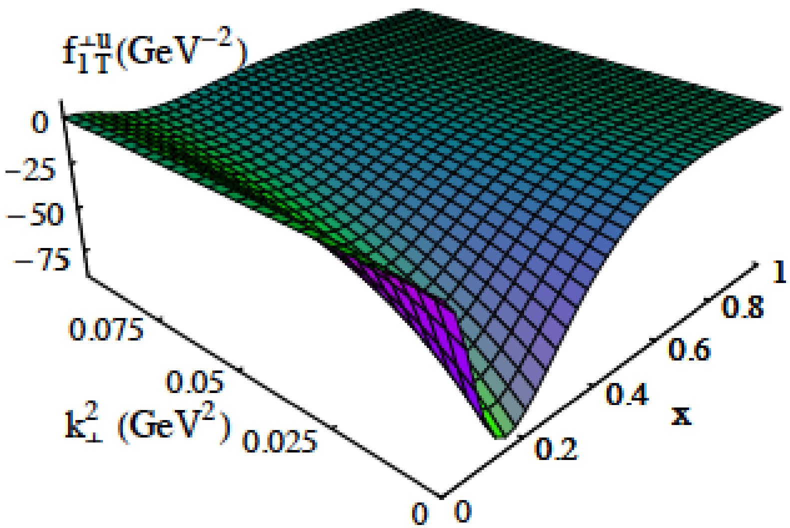
If unfavored Collins fragmentation dominates measured π- vs π+, why K- vs K+ is different?

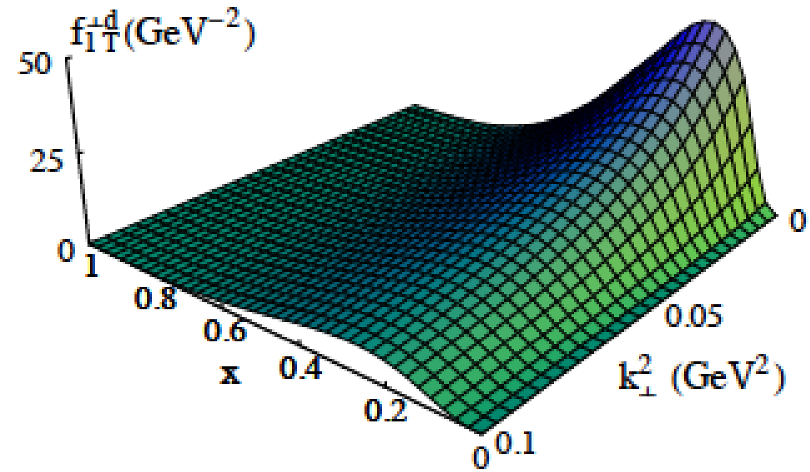
SIDIS ($\gamma^* p \to \pi X$) : Transversely polarized target

- 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





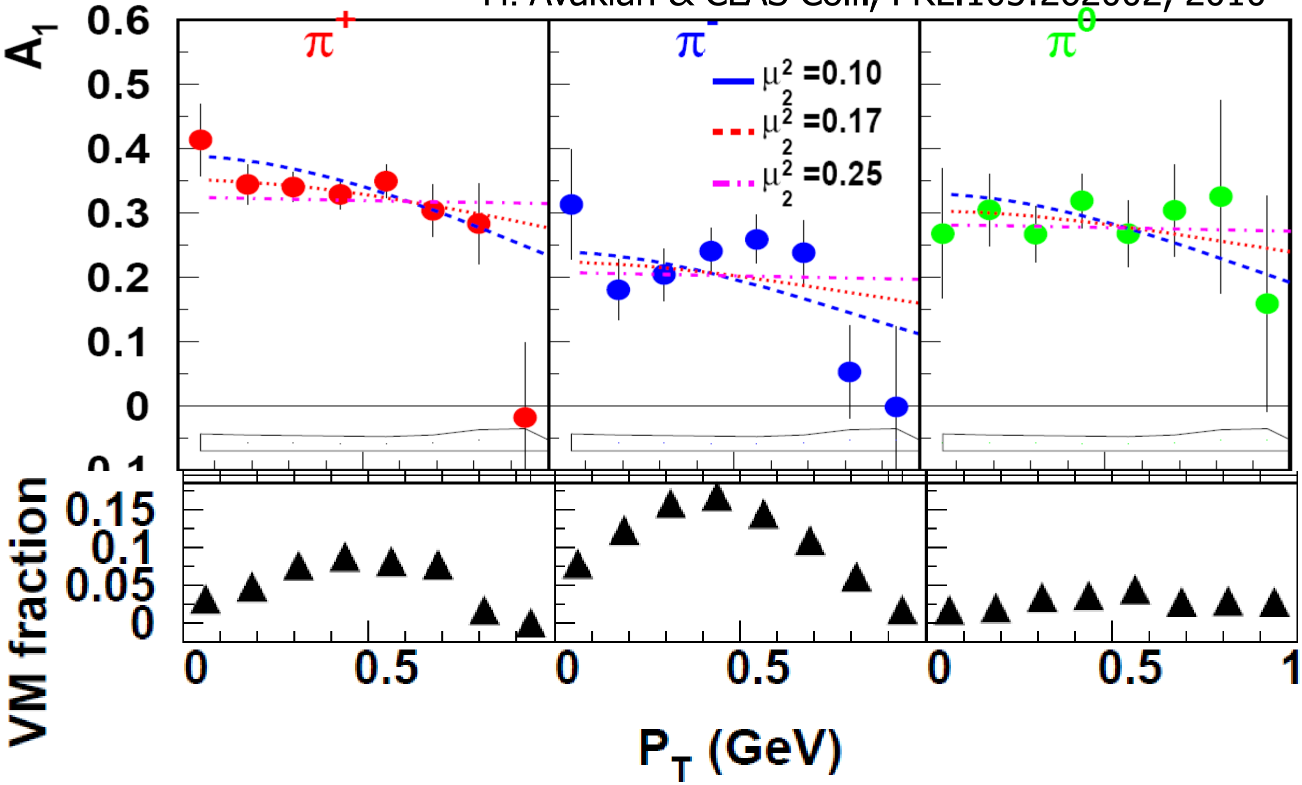
$A_1 - P_T$ dependence

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 $h_{1T}^\perp$

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

0.4<z<0.7

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

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

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

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

π^+ A_1 suggests broader k_T distributions for f_1 than for g_1

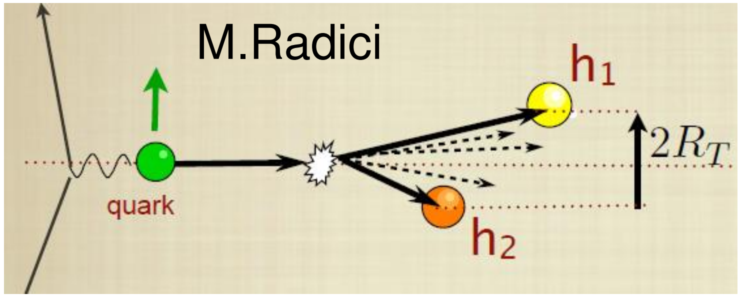
π^- A_1 may require non-Gaussian k_T-dependence for different helicities and/or flavors

HT-distributions and dihadron SIDIS

Compare single hadron and dihadron SSAs

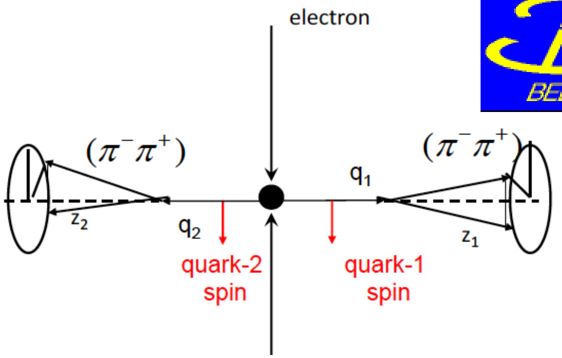
$$\frac{M}{M_h}\, x\, e(x)\, H_1^{\sphericalangle}(z,\zeta,M_h^2) + \frac{1}{z} f_1(x)\, \widetilde{G}^{\sphericalangle}(z,\zeta,M_h^2)$$

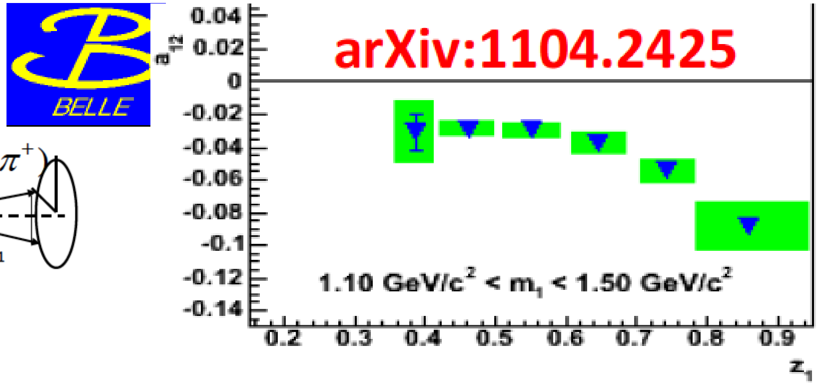
$$\frac{M}{M_h}\, x\, h_L(x)\, H_1^{\sphericalangle}(z,\zeta,M_h^2) + \frac{1}{z} g_1(x)\, \widetilde{G}^{\sphericalangle}(z,\zeta,M_h^2)$$



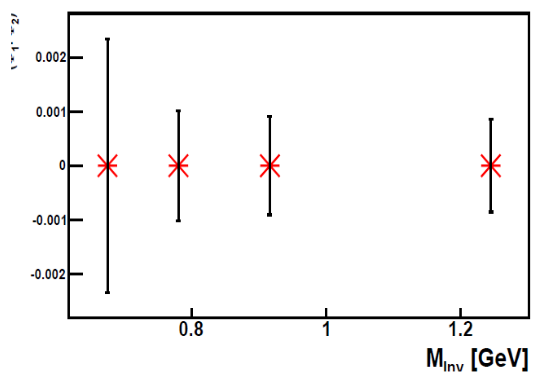
Only 2 terms with common unknown HT G~ term!

Aurore Courtoy/Anselm Voosen - Spin session





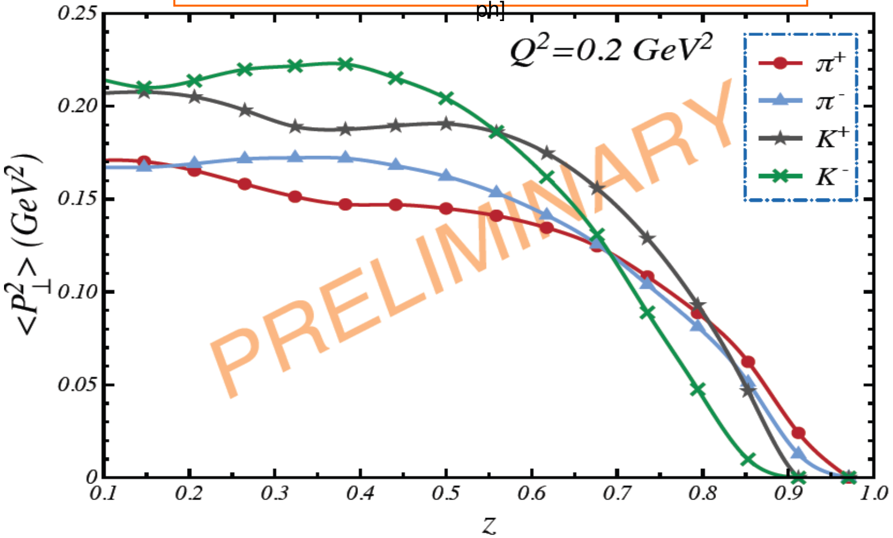
Projections for (π^+K^-) $(K^+\pi^-)$ for 580 fb^{-1}



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

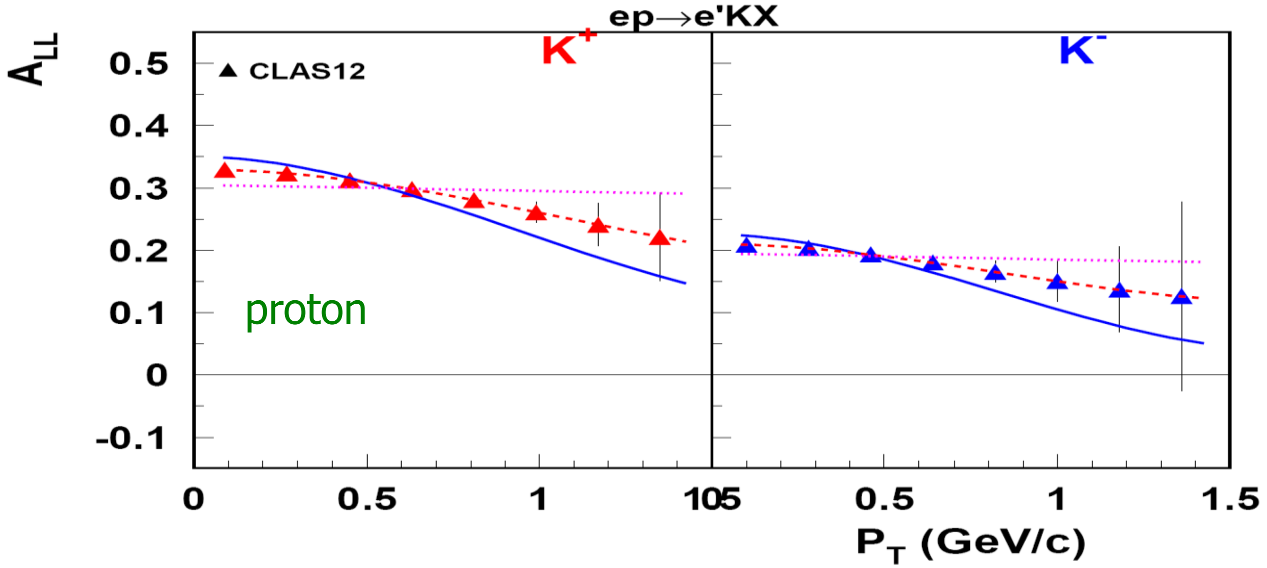
Transverse momentum distributions of partons

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 $H_1^\perp$

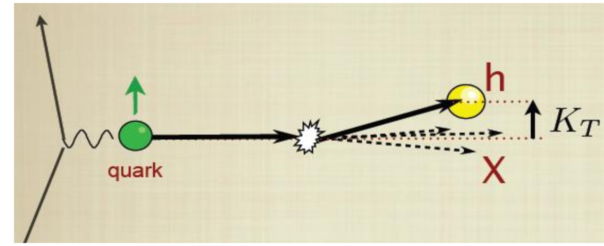
$$F \equiv \sigma_{UL}^{\sin 2\phi}, \sigma_{UU}^{\cos 2\phi}, \ldots.$$

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

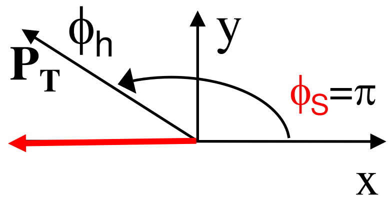
Combined analysis of Collins fragmentation asymmetries from proton and deuteron and for π and K may provide independent to e^+e^- (BELLE/BABAR) information on the underlying Collins function.

Chiral odd HT-distribution

How can we separate the HT contributions?



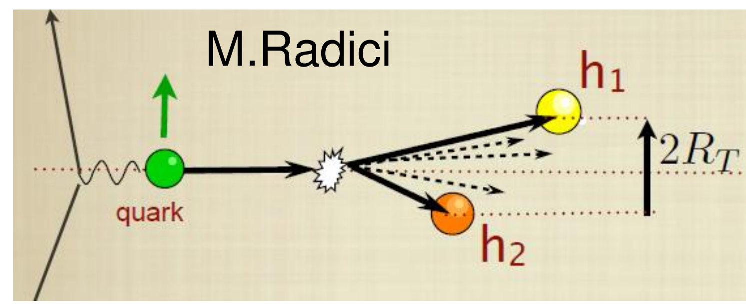
$F_{LU}^{\sin\phi}$ $F_{UL}^{\sin\phi}$



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

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

Compare single hadron and dihadron SSAs

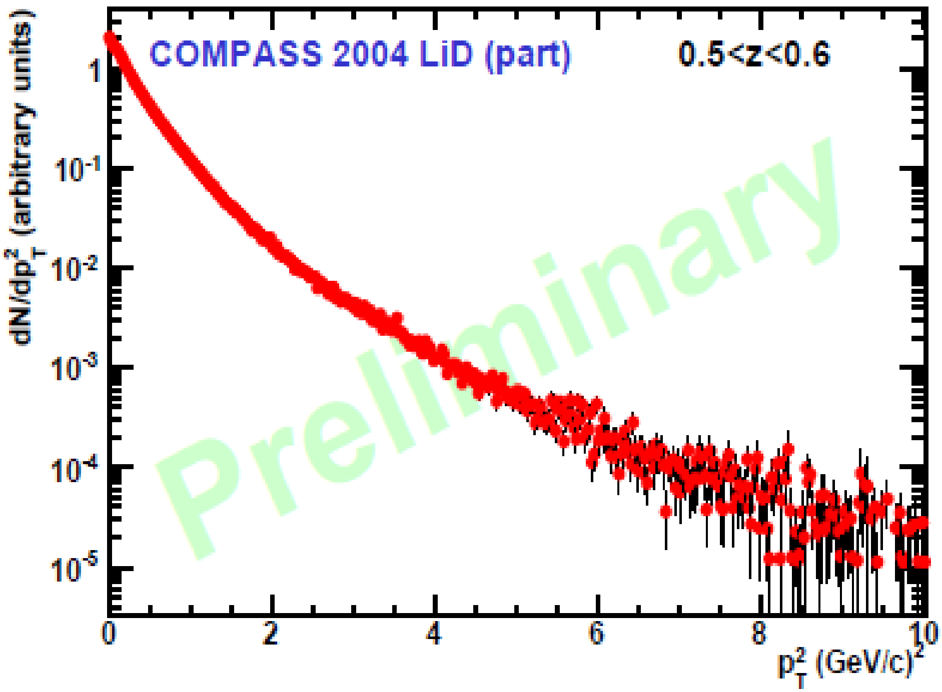


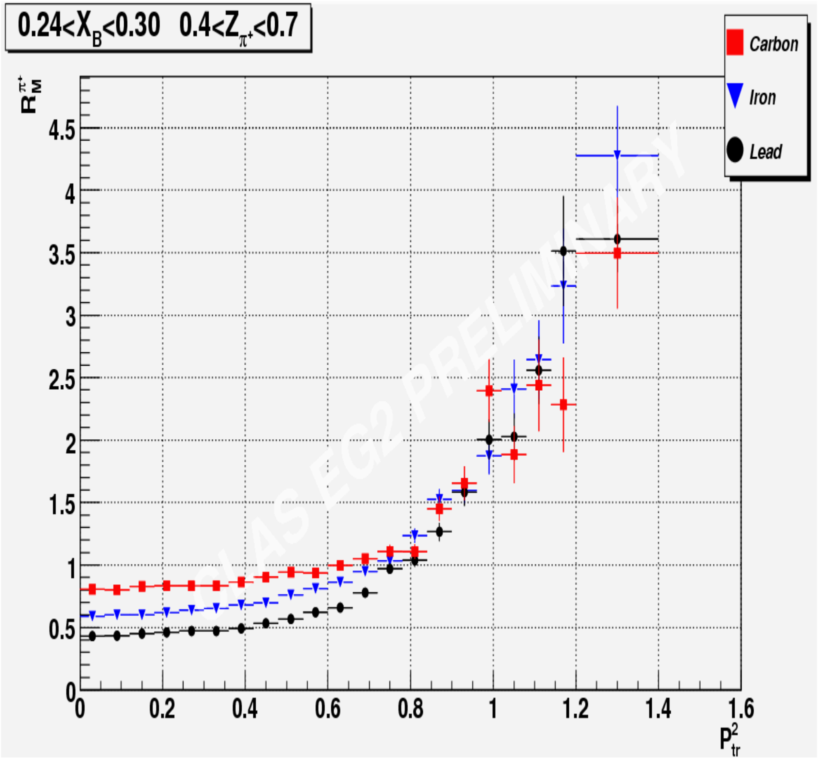
$$\frac{M}{M_h}\,x\,e(x)\,H_1^{\sphericalangle}(z,\zeta,M_h^2)+\frac{1}{z}\,f_1(x)\,\widetilde{G}^{\sphericalangle}(z,\zeta,M_h^2)$$

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

Only 2 terms with common unknown HT G~ term!

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

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

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	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

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

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

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

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

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

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

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

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, $h_T^\perp$, $e_T^\perp$

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

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"

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 ,$h_T^\perp$, $e_T^\perp$

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

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

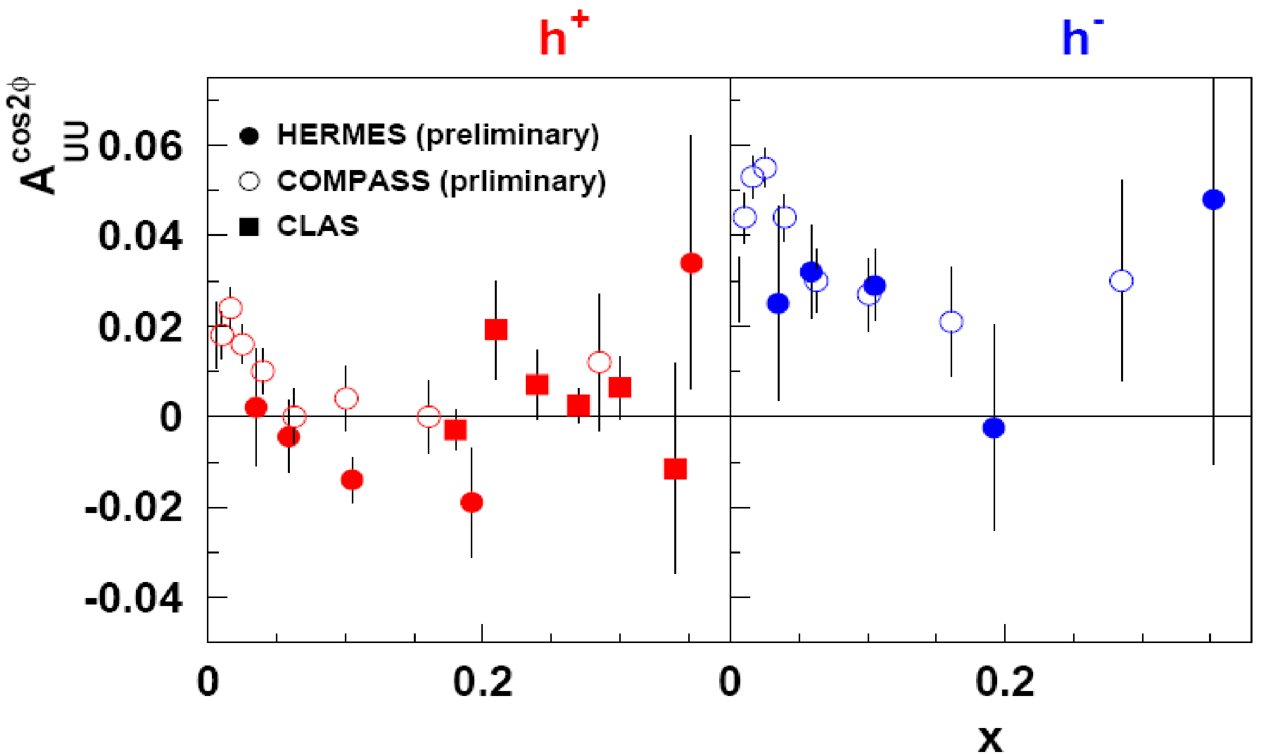
$$\frac{1}{2Mx}\,\mathrm{Tr}\left[\tilde{\Phi}_{A\rho}(g_T^{\alpha\rho} + i\epsilon_T^{\alpha\rho}\gamma_5)\gamma^+\right] = \frac{p_T^\alpha}{M}(\tilde{f}^\perp - i\tilde{g}^\perp) - \epsilon_T^{\alpha\rho}\,S_{T\rho}\,(\tilde{f}_T + i\tilde{g}_T)$$
$$- S_L\,\frac{\epsilon_T^{\alpha\rho}\,p_{T\rho}}{M}\,(\tilde{f}_L^\perp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

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

TMD PDFs

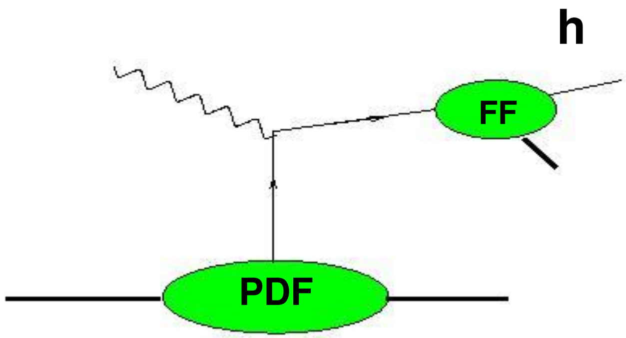
$$\frac{d\sigma}{dx\,dy\,dz\,d^2\vec{P}_h} = \frac{4\pi\alpha^2 s}{Q^4}[x(1-y+y^2/2)F_{UU} \longrightarrow f_1 D_1$$

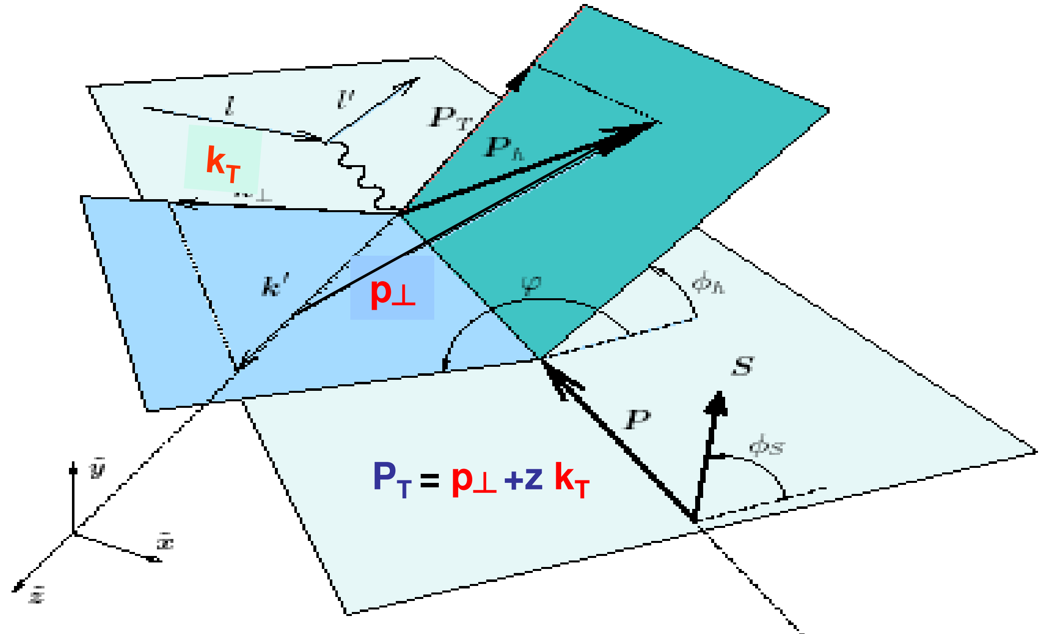
$$-x(1-y)\cos(2\phi)F_{UU}^{\cos 2\phi}] \longrightarrow h_1^{\perp} H_1^{\perp}$$



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

SIDIS: partonic cross sections



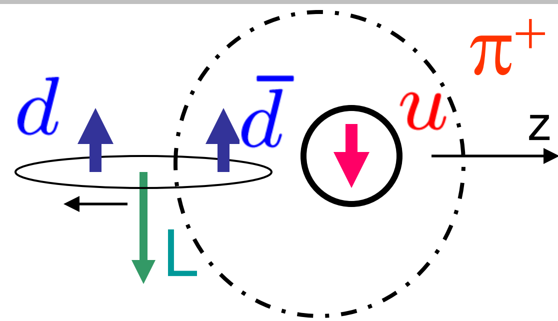


$$d\sigma^h \propto \sum f^{H\to q}(x, k_T) \otimes \mathbf{d}\sigma_q(y) \otimes D^{q\to h}(z, p_\perp)$$

$$d\sigma^h \propto \sum f^{H\to q}(x)\mathbf{d}\sigma_q(y) D^{q\to h}(z)$$

Collins effect

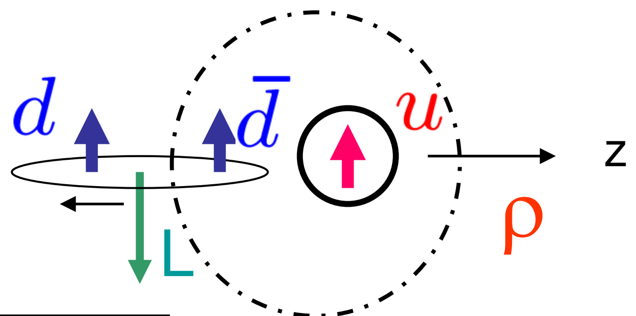
Simple string fragmentation for pions (Artru model)



leading pion out of page

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

ρ production may produce an opposite sign A_{UT}



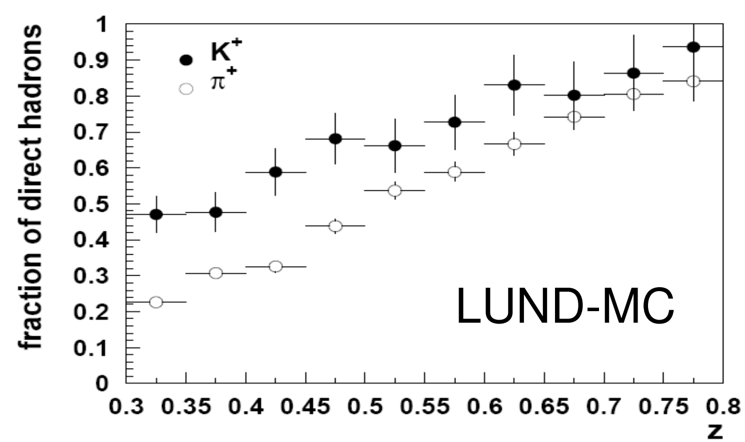
Leading ρ opposite to leading π(into page)

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

hep-ph/9606390

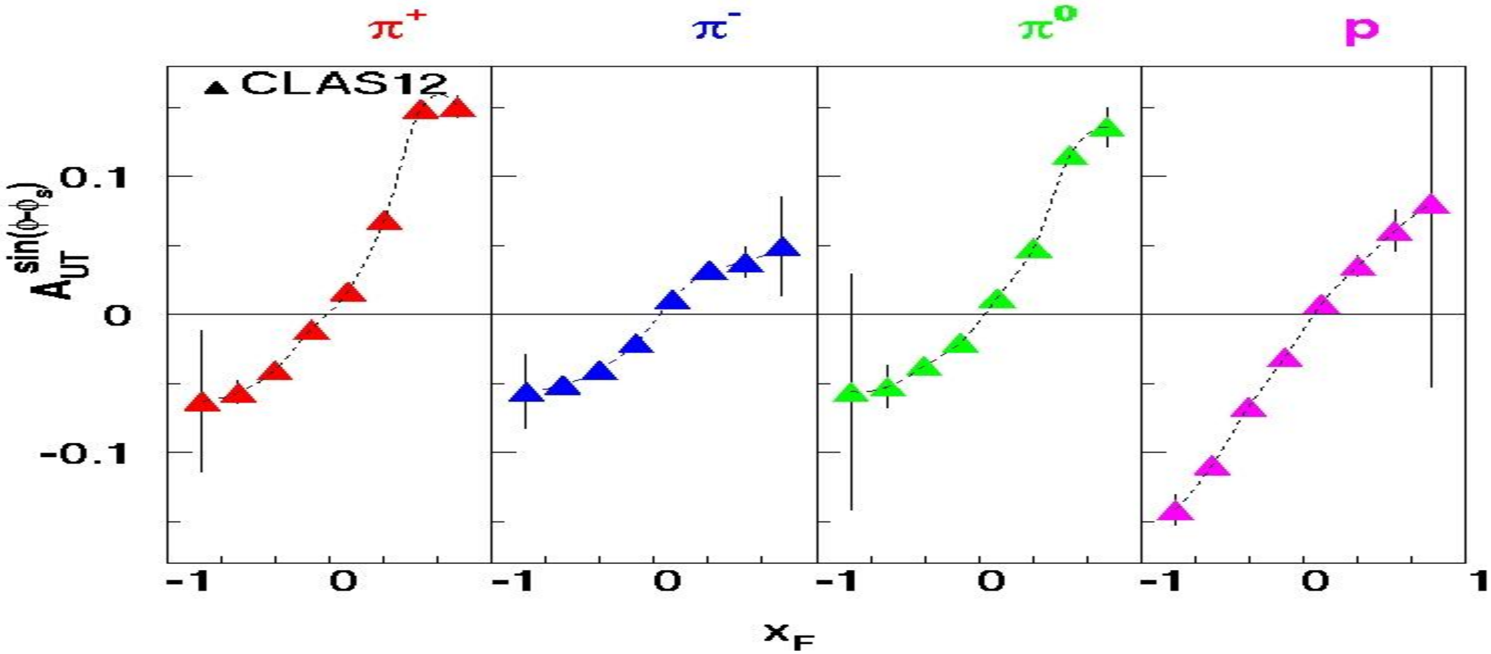
Fraction of ρ in eπX	% left from eπX asm
20%	~75%
40%	~50%

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



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

$$q(x,k_\perp)|_{k_\perp \gg \Lambda_{\rm QCD}} = \frac{1}{(k_\perp^2)^n}\int \frac{dx'}{x'} f_i(x') \times \mathcal{H}_{q/i}(x;x') \ , \qquad (23$$

where $q(x,k_\perp)$ represents the TMD quark distribution we are interested, f_i represents the in tegrated quark distribution for the $k_\perp$-even TMDs, and higher twist quark-gluon correlatio function for the $k_\perp$-odd TMDs. For the latter case, x' should be understood as two variable for the twist-three quark-gluon correlation functions as we discussed in the last section. Th overall power behavior $1/(k_\perp^2)^n$ can be analyzed by the power counting rule [48]. The har coefficient $\mathcal{H}_{q/i}(x;x')$ is calculated from perturbative QCD. In this paper, we will show th one-gluon radiation contribution to this hard coefficient.

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

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

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

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

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

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 $h_{1T}^\perp$

Large-x limit

Brodsky & Yuan (2006)

Burkardt (2007)

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

Large-Nc limit (Pobilitsa)

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

Do not change sign (isoscalar)

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

All others change sign
u→d (isovector)