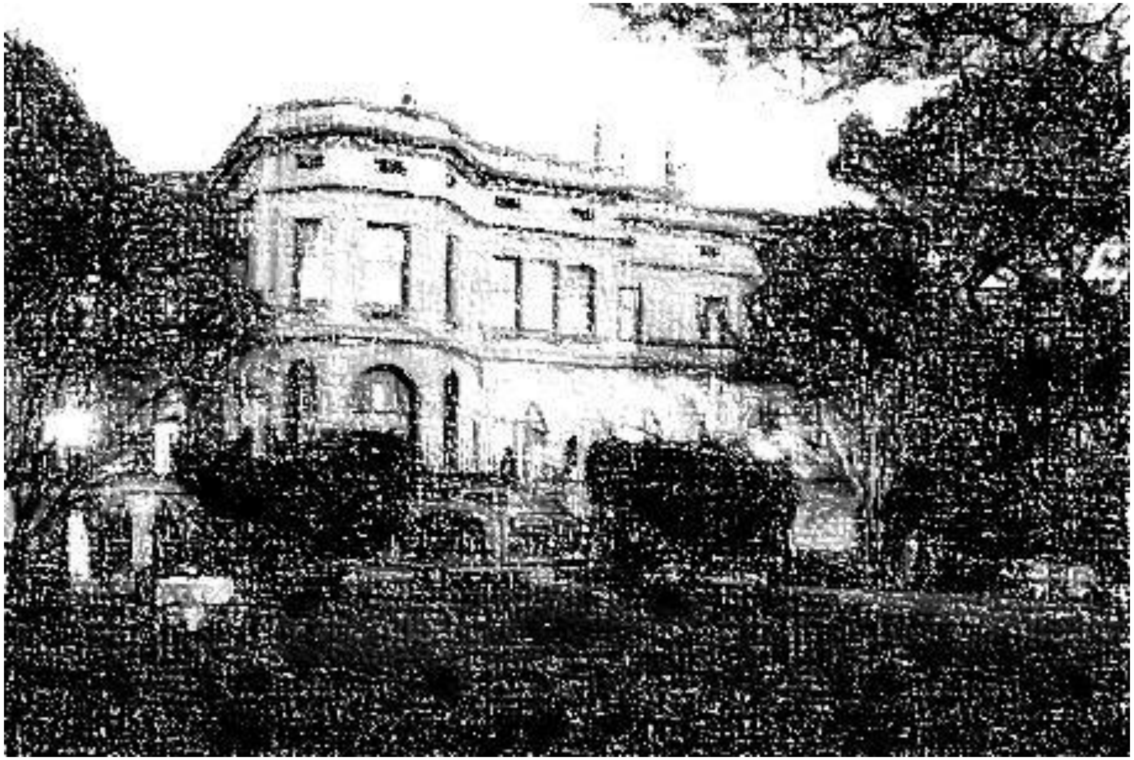
Latest TMD measurements from Hall-B@JLab



Silvia Pisano

Laboratori Nazionali di Frascati - INFN

QCD-N'16@Getxo, Bilbao - July 12th, 2016

Exploring the nucleon valence structure

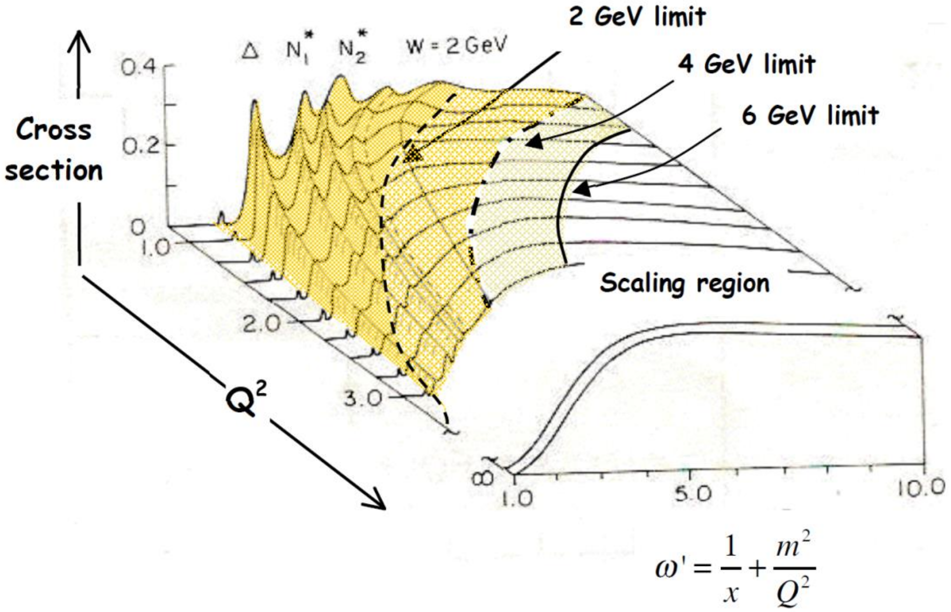
How do the QCD Lagrangian degrees of freedom relate to the hadrons we observe?

At what energy the partonic interpretation does start to emerge?

How do the spin and the mass of the nucleon emerge from its constituents characteristics?

How does the nucleon picture change with the resolution of the hard probe?

What is the role of the *strange sea* in the nucleon?



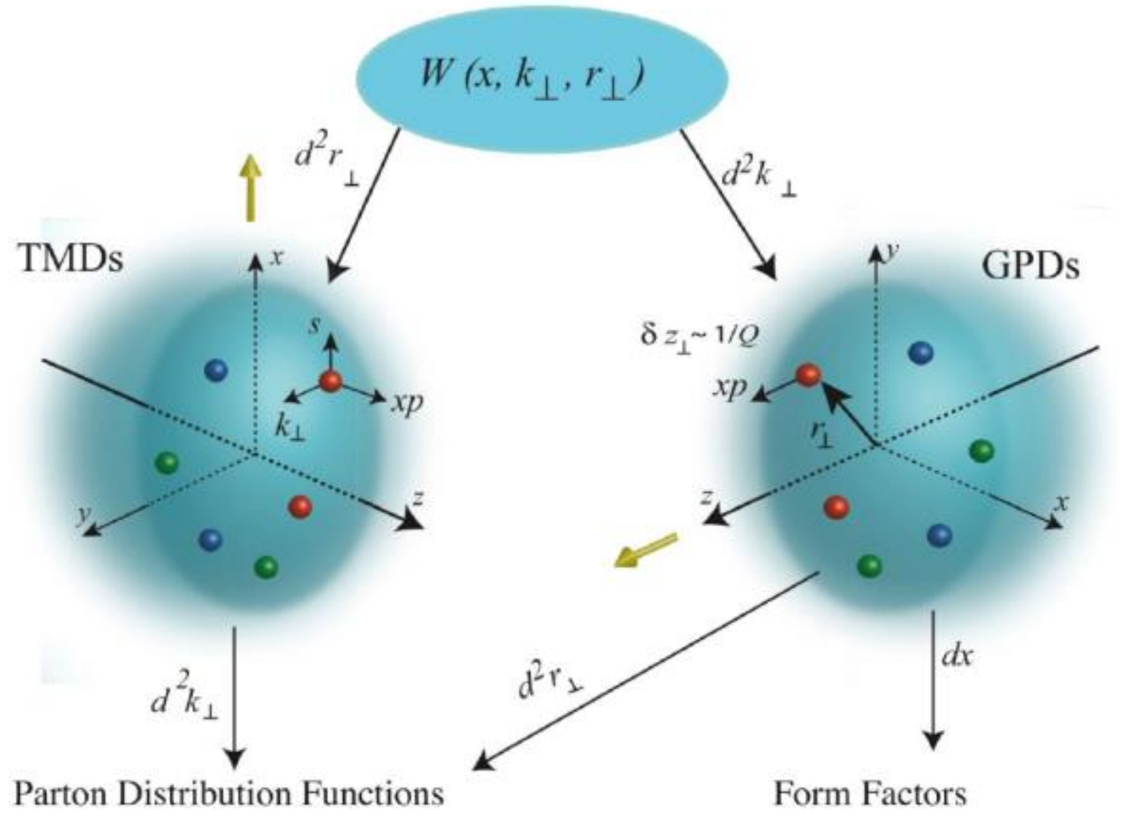
$$\omega' = \frac{1}{x} + \frac{m^2}{Q^2}$$

F. Gross, «Making the case for Jefferson Lab»
The first decade of Science at Jefferson Lab
JoP, Conf. Series 299 (2011) 012001

5D mapping of the nucleon

Wigner «Mother» functions are quantum-phase distributions of quarks

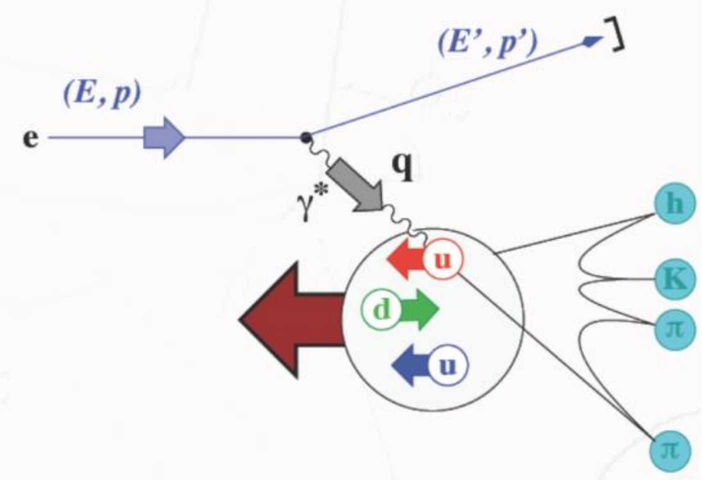
→ ***not directly accessible with today's available means, we can only extract their 3D reductions***

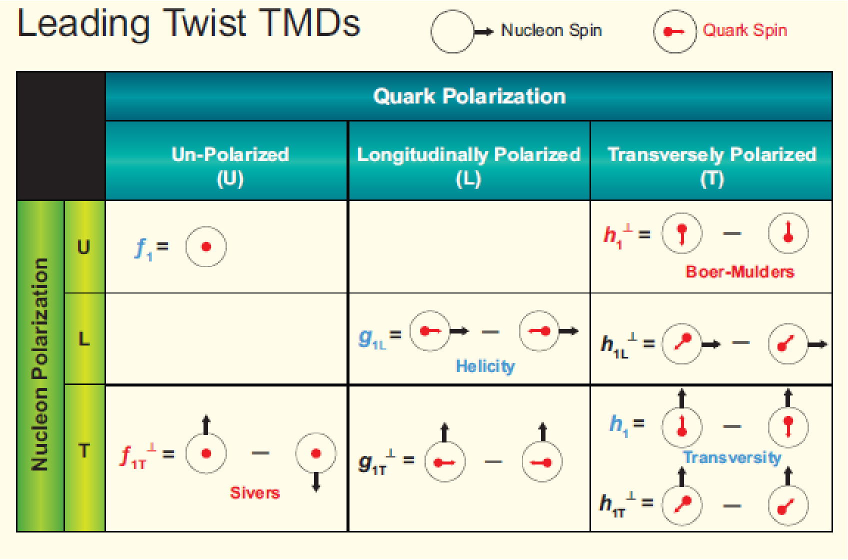


Tranverse Momentum Distributions

8 leading-twist TMDs

They depend on the parton longitudinal fraction x and on its transverse momentum k_T → ***full 3D dynamics***





Leading Twist TMDs ○→ Nucleon Spin ⊖ Quark Spin

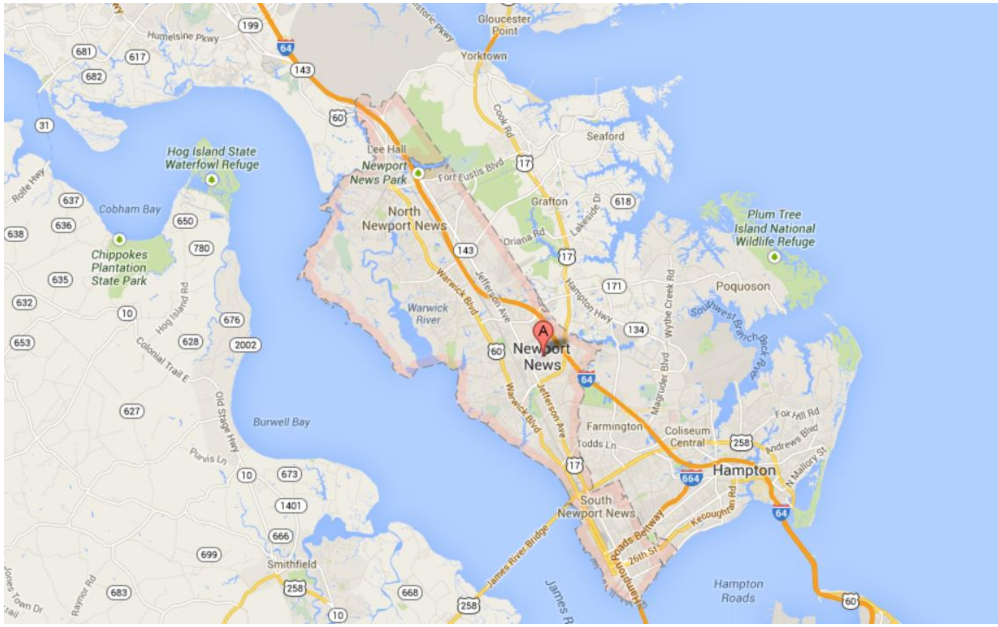
		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	f_1 = ⊙		$h_1^\perp$ = ○ − ○ Boer-Mulders
	L		g_{1L} = ○→ − ○→ Helicity	$h_{1L}^\perp$ = ○→ − ○→
	T	$f_{1T}^\perp$ = ○ − ○ Sivers	$g_{1T}^\perp$ = ○ − ○	h_1 = ○ − ○ Transversity $h_{1T}^\perp$ = ○ − ○

Fragmentation Functions → transition from partonic to hadronic degrees of freedom

q/H	U	L	T
U	$\boldsymbol{D_1}$		$H_1^\perp$
L		$\boldsymbol{G_{1L}}$	$H_{1L}^\perp$
T	$H_1^\perp$	G_{1T}	$\boldsymbol{H_1}$, $H_{1T}^\perp$

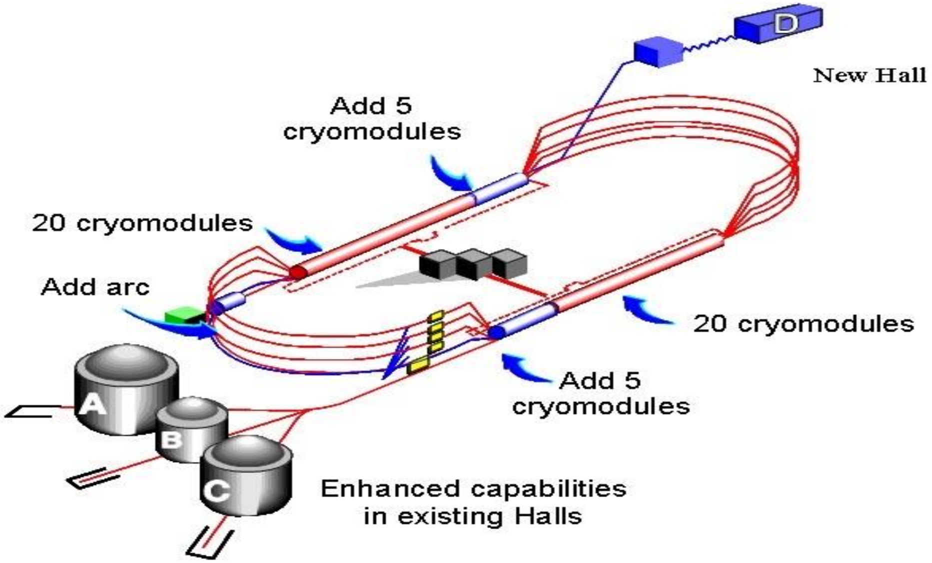
Jefferson Lab

- provides a continuous electron beam with a duty factor ~ 100%;
- with a beam energy up to **6 GeV**;
- has a good energy resolution ($\frac{\sigma_E}{E} \sim 10^{-5}$);
- and the beam has a polarization ~ 85%

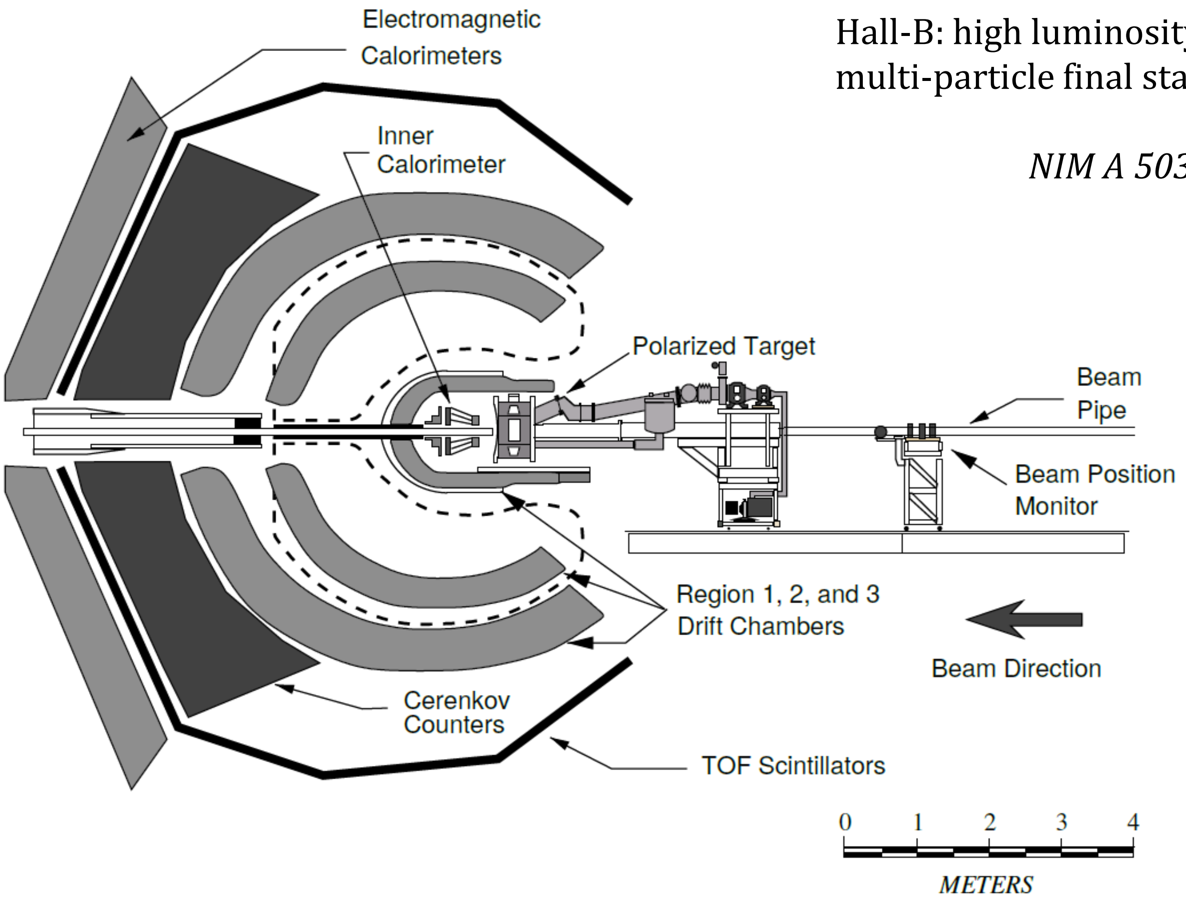


Jefferson Lab

- ○ provides a continuous electron beam with a duty factor ~ 100%;
- ○ with a beam energy up to **12 GeV**;
- ○ has a good energy resolution ($\frac{\sigma_E}{E} \sim 10^{-5}$);
- ○ and the beam has a polarization ~ 85%



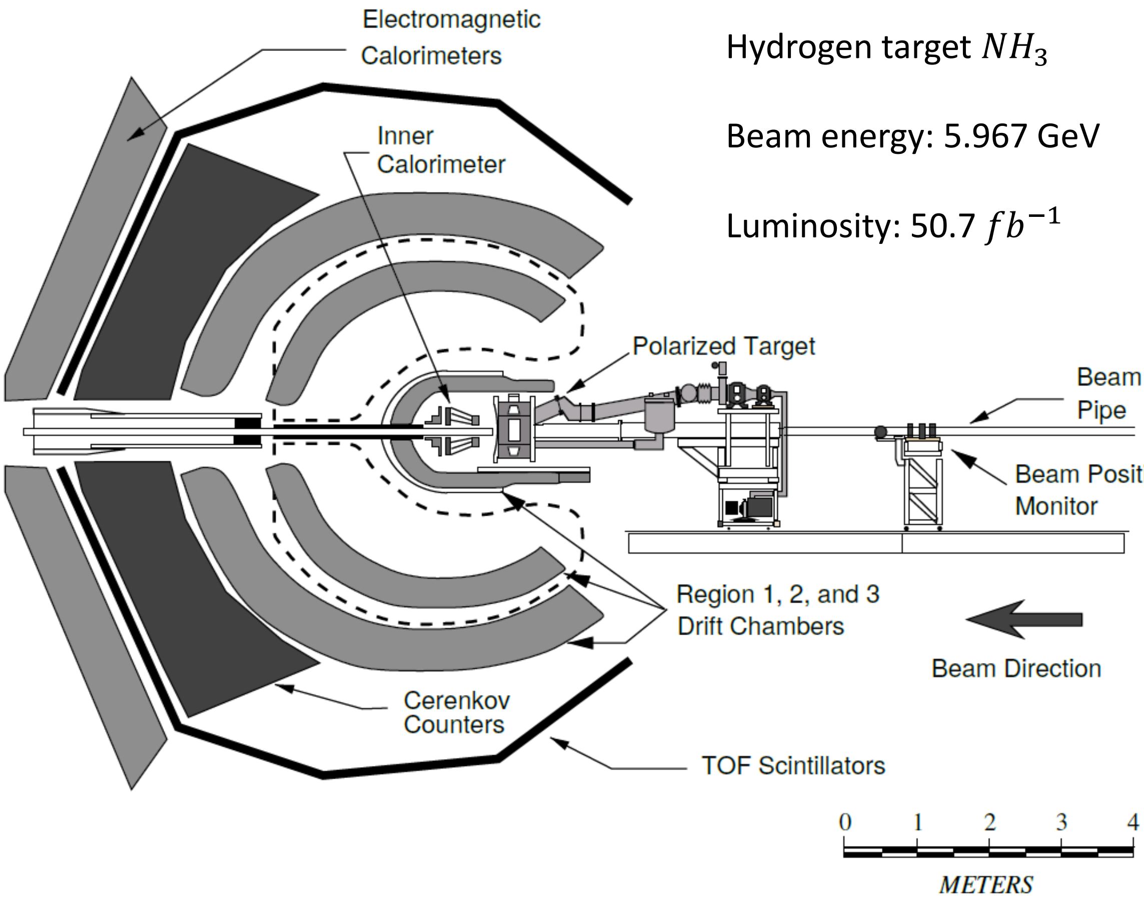
Hall-B@Jefferson Lab (the CLAS detector)



Hall-B: high luminosity, large acceptance, multi-particle final state measurements

NIM A 503, 513 (2003)

TMDs with a longitudinally-polarized target



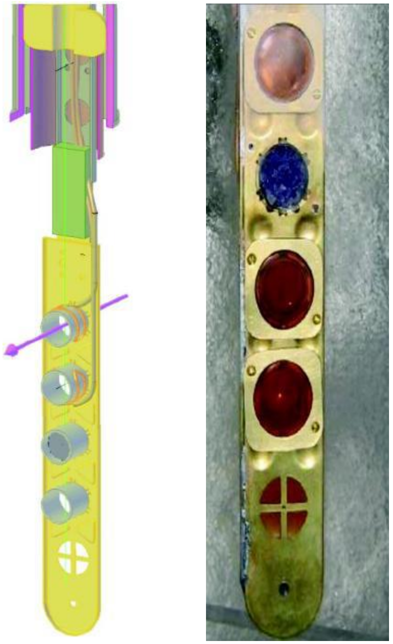
Longitudinally-polarized ^{3}NH

Hydrogen target NH_3

Beam energy: 5.967 GeV

Luminosity: 50.7 fb^{-1}

*C.D. Keith et al., NIM A 501 (2003) 327



Proton polarizations

$P^{\uparrow} = 82\%$

$P^{\downarrow} = 75\%$

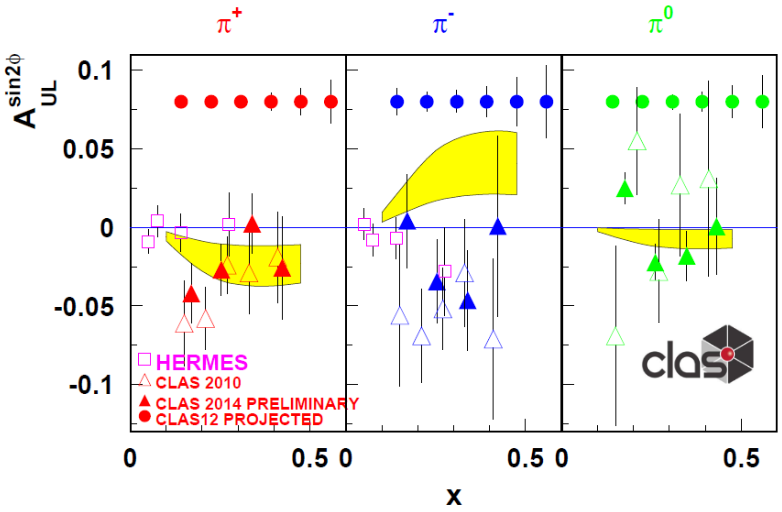
Check of Collins effects through $A_{UL}{}^{\sin 2\varphi}$

A_{UL} and A_{LL} for $\pi^{\pm}$ production
(2001 data)

A_{UL}: Kotzinian-Mulder function → tranversely-polarized quark in a longitudinally-polarized proton

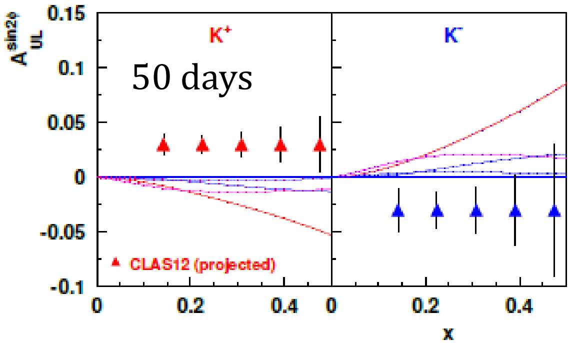
$$F_{UL}{}^{\sin 2\varphi} \propto h_{1L}{}^{\perp} \otimes H_1{}^{\perp}$$

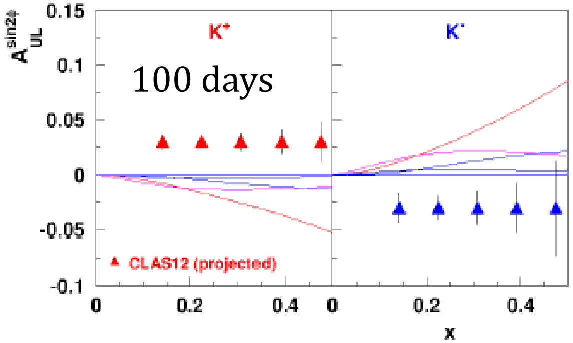
First measurement of non-zero $A_{UL}{}^{\sin 2\varphi}$ for pions → potentially significant quark spin-orbit correlations



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

@12 GeV





Check of Collins effects through $A_{UL}^{\sin 2\varphi}$

A_{UL} and A_{LL} for $\boldsymbol{\pi^0}$ production
(2009 data)

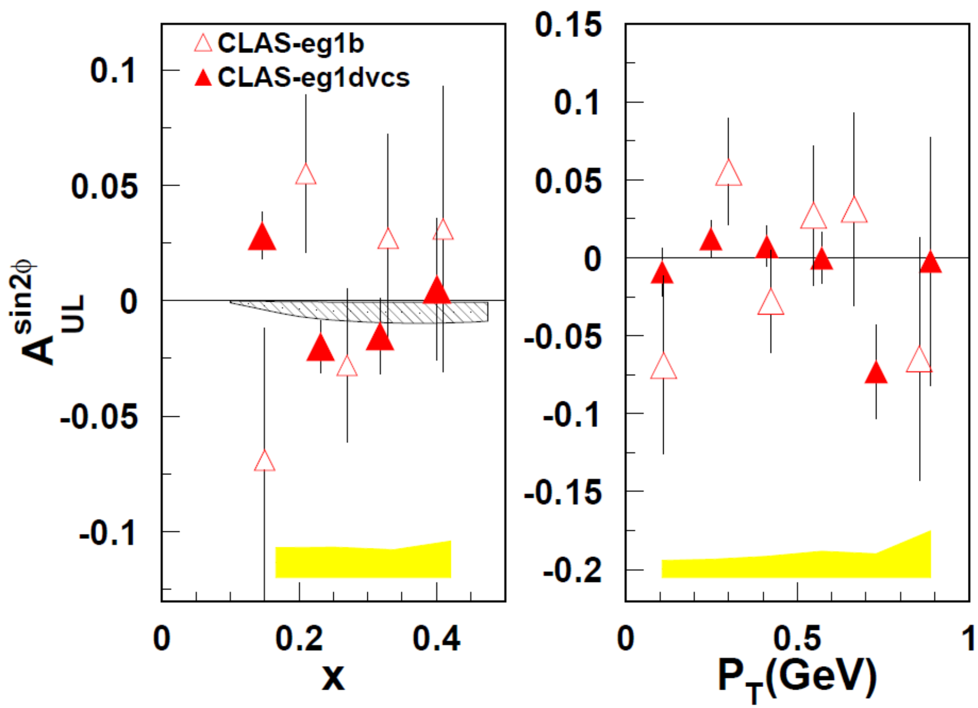
N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	$h_1 \; h_{1T}^{\perp}$

A_{UL}: Kotzinian-Mulder function → tranversely-polarized quark in a longitudinally-polarized proton

$$F_{UL}^{\sin 2\varphi} \propto h_{1L}^{\perp} \otimes H_1^{\perp}$$

e^+e^- machines indicate that $H_1^{\perp}$ is large with opposite sign for favored and unfavored FF → ***expected significant suppression for*** $\boldsymbol{\pi^0}$

$A_{UL}^{\sin 2\varphi}$ → consistent with zero, confirming the Collins dominating scenario



Check of Collins effects through $A_{UL}^{\sin\varphi}$

A_{UL} and A_{LL} for π^0 production
(2009 data)

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

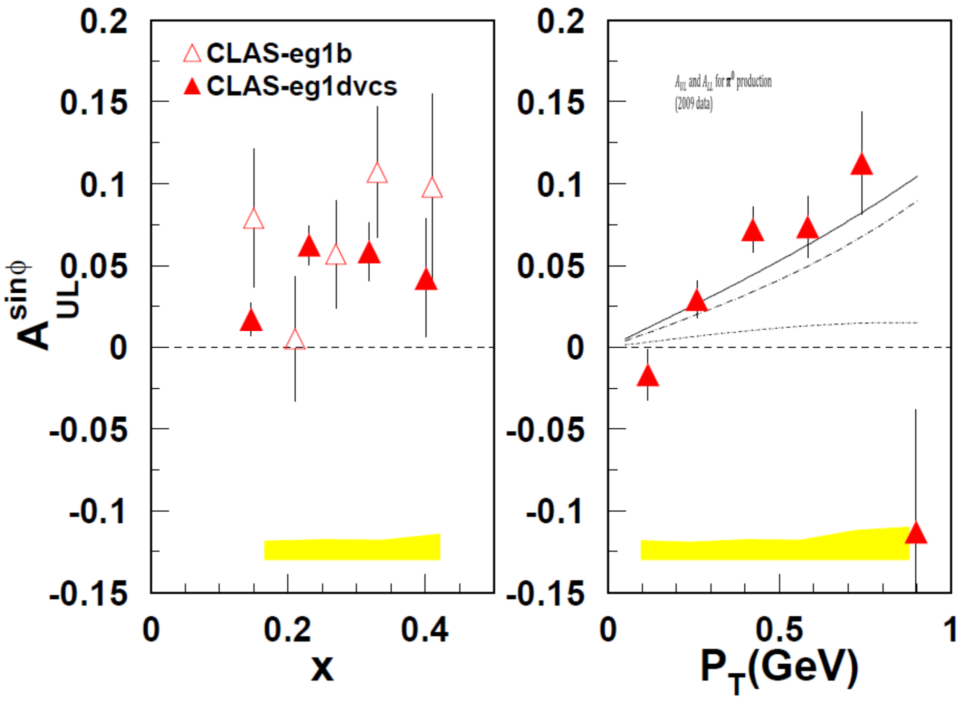
$A_{UL}^{\sin\varphi}$ → Entire structure function is twist-3, so in commonly used Wandzura-Wilczek approximation entire asymmetry = 0

Collins-type or Sivers-type terms are present

Dotted-lines: Collins-type contributions

Dashed: Sivers-type contributions

W. Mao and Z. Lu, Phys. Rev. **D87**, 014012 (2013), 1210.4790.
Z. Lu and W. Mao, Int. J. Mod. Phys. Conf. Ser. **40**,

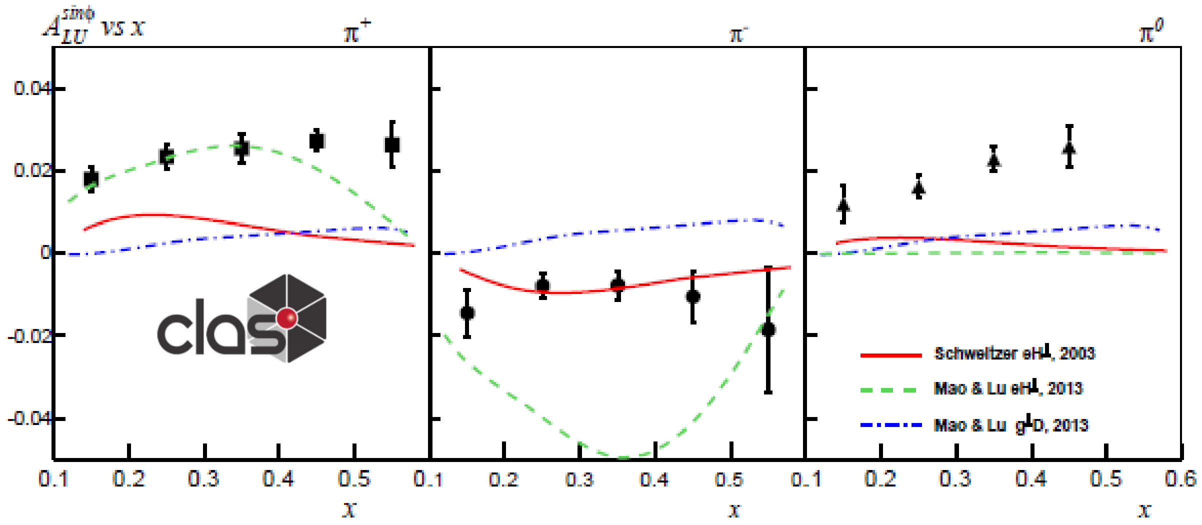


Check of Collins effects through $A_{LU}{}^{\sin\varphi}$

→ Entire structure function is twist-3, so in commonly used Wandzura-Wilczek approximation entire asymmetry = 0

$$F_{LU}{}^{\sin\varphi} \propto e \otimes H_1{}^{\perp} + f_1 \otimes \tilde{G}^{\perp} + g^{\perp} \otimes D_1 + h_1{}^{\perp} \otimes \tilde{E}$$

$e(x)$: twist-3 PDF sensitive to qGq correlations



Schweitzer *et al*, $eH_1{}^{\perp}$ (2003)

Mao & Lu, $eH_1{}^{\perp}$ (2013)

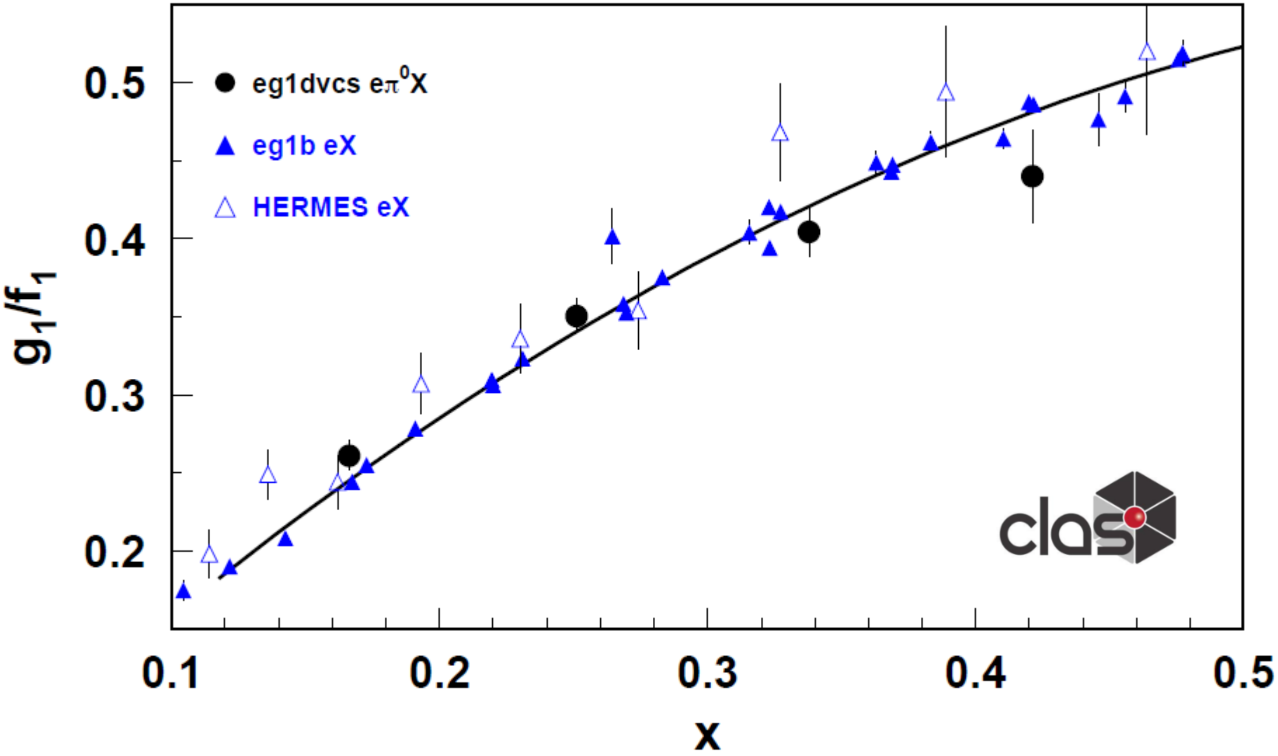
Mao & Lu, $g^{\perp}D$ (2013)

W. Gohn *et al.*, PRD89, 072011 (2014)@5.5 GeV

Neutral pion A_{LL}: partonic picture

In a ***simple parton model***, at large x, where the sea and strange quark contributions are negligible, π^0 A_{LL} is expected to be identical to the inclusive case, due to cancellation of fragmentation function in the nominator and denominator.

double spin asymmetries measured at relatively low energies covered by JLab are consistent with a simple partonic picture.



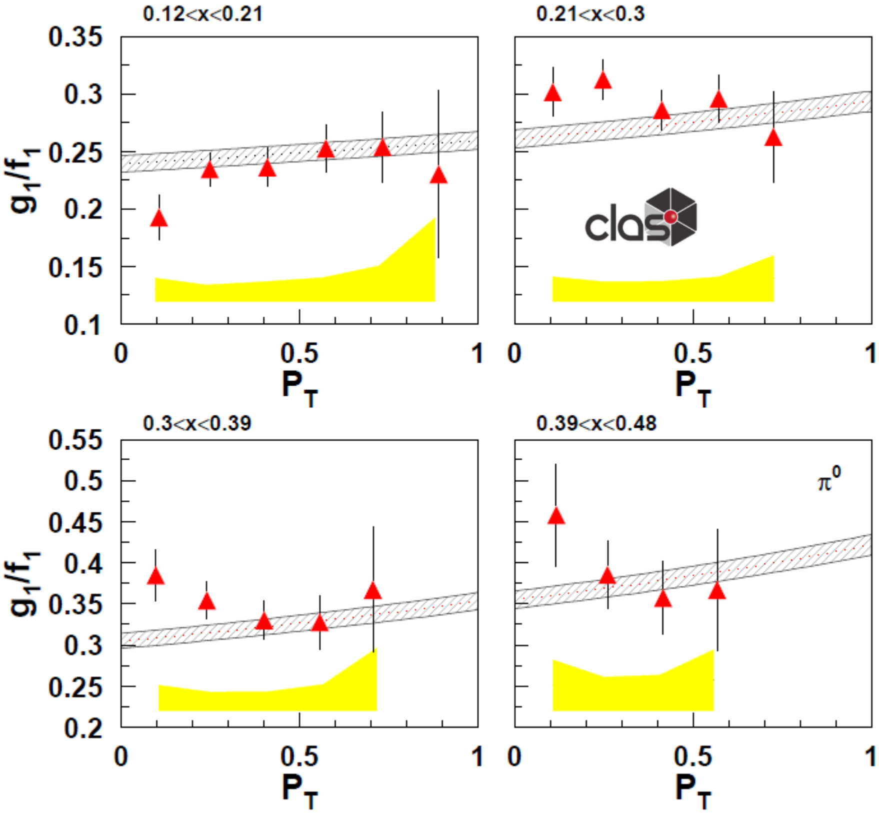
A partonic picture

In a ***simple parton model***, at large x, where the sea and strange quark contributions are negligible, π^0 A_{LL} is expected to be identical to the inclusive case, due to cancellation of fragmentation function in the nominator and denominator.

double spin asymmetries measured at relatively low energies covered by JLab are consistent with a simple partonic picture.

Stochastical Parton Model (Soper *et al*):

non-trivial k_T dependence → observed P_T dependence

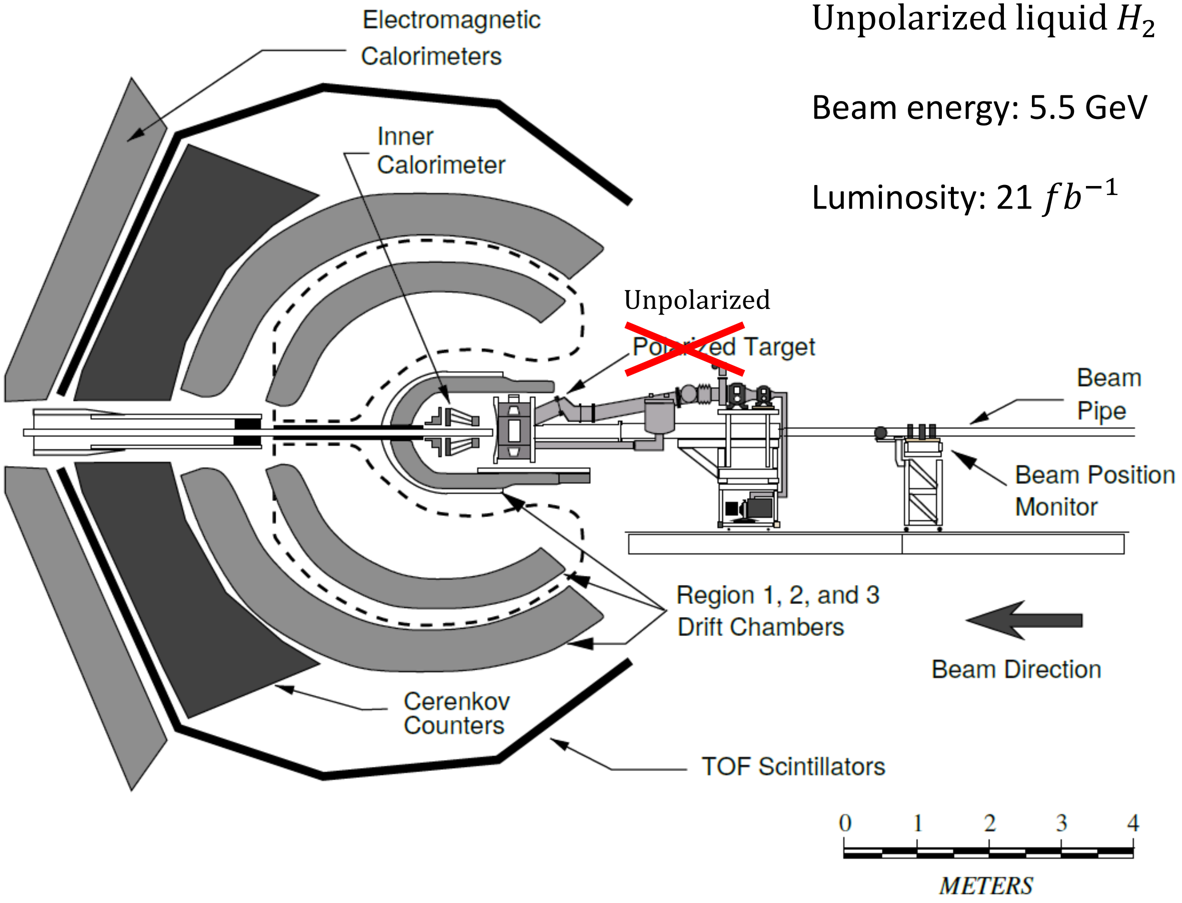


TMDs with an unpolarized target

Unpolarized liquid H_2

Beam energy: 5.5 GeV

Luminosity: 21 fb^{-1}



Azimuthal distributions in SIDIS

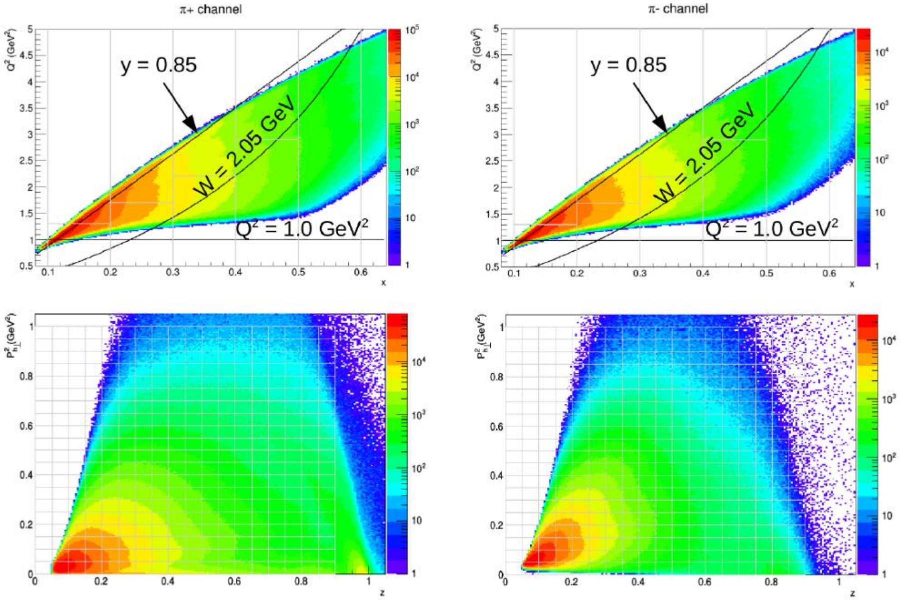
$f_1 \otimes D_1$

$$\frac{d^5\sigma}{dx\,dQ^2\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{2\pi}{2(k\cdot P)x}\,\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\{F_{UU,T}+\varepsilon F_{UU,L} + \sqrt{2\varepsilon\,(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos\left(2\phi_h\right) F_{UU}^{\cos 2\phi_h}\}$$

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

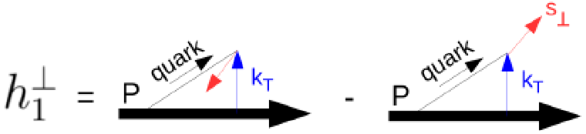
f_1 : unpolarized quark inside an unpolarized nucleon

$h_1{}^{\perp}$: transversely-polarized quark inside an unpolarized nucleon → it quantifies spin-orbit correlations, thus requiring non-zero orbital angular momentum

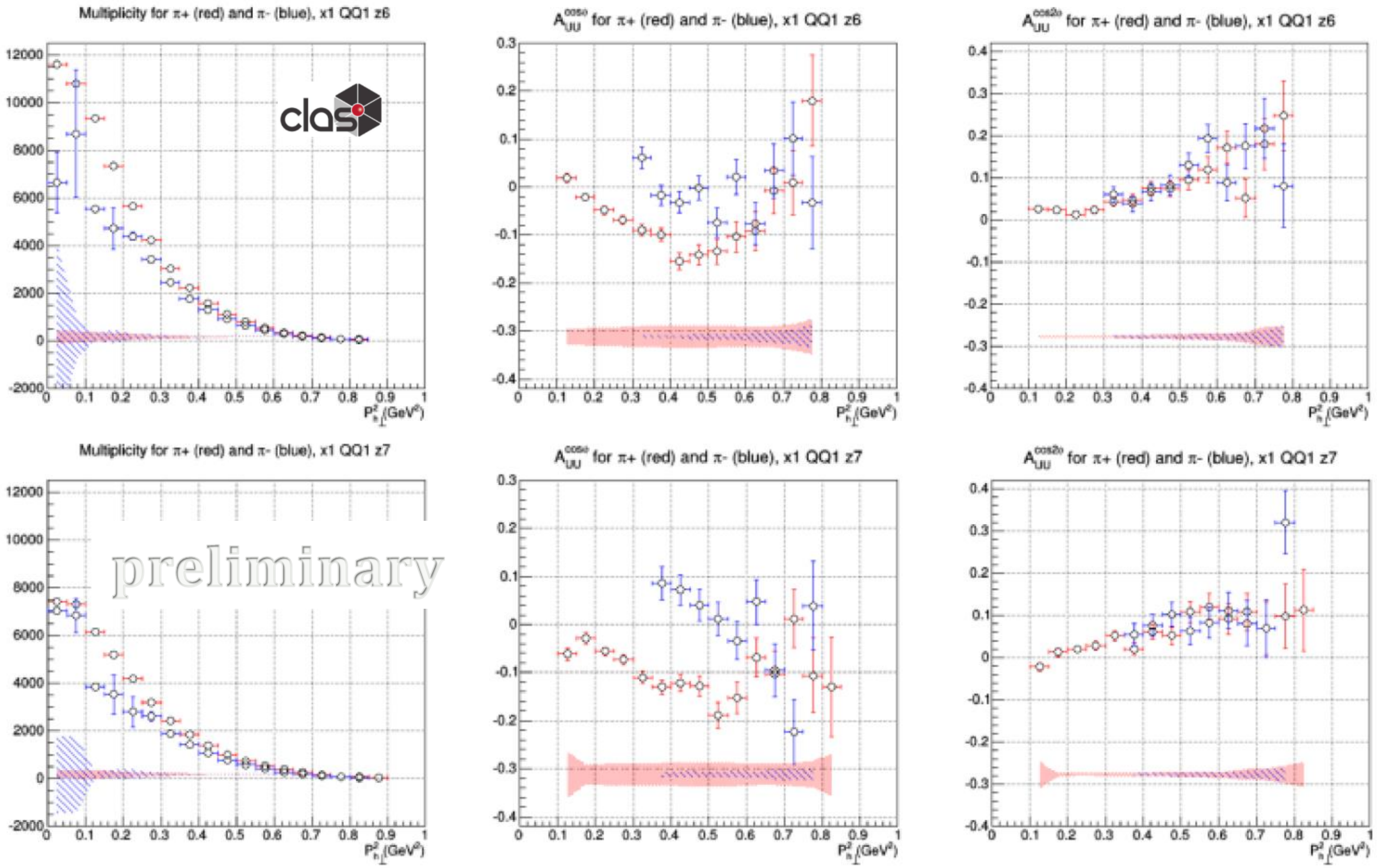


N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	$h_1\ \ h_{1T}^{\perp}$

Boer-Mulder function



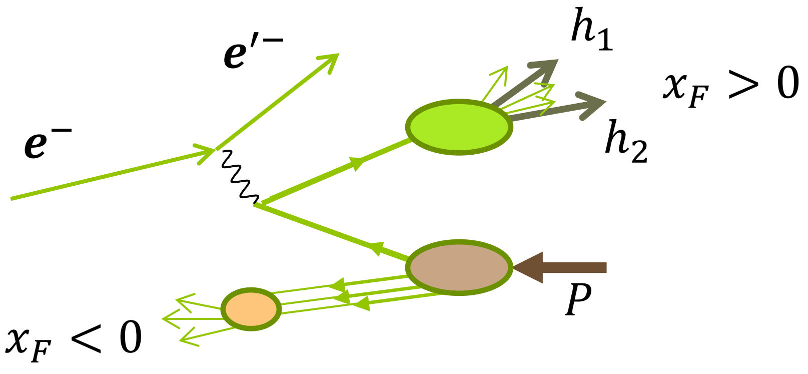
Azimuthal distributions in SIDIS

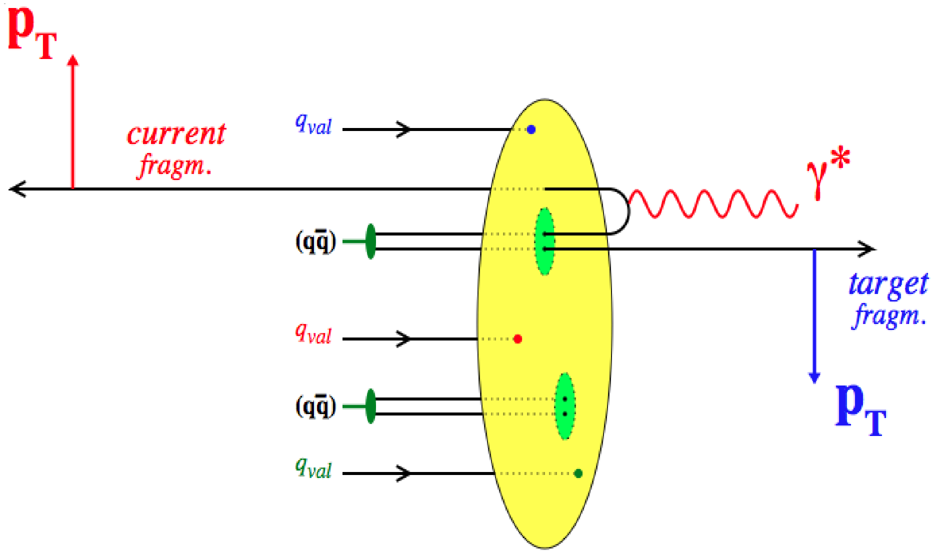


$A_{UU}{}^{\cos\varphi}$ and $A_{UU}{}^{\cos 2\varphi}$ show a dependence on the flavor → non-zero Boer-Mulders effect

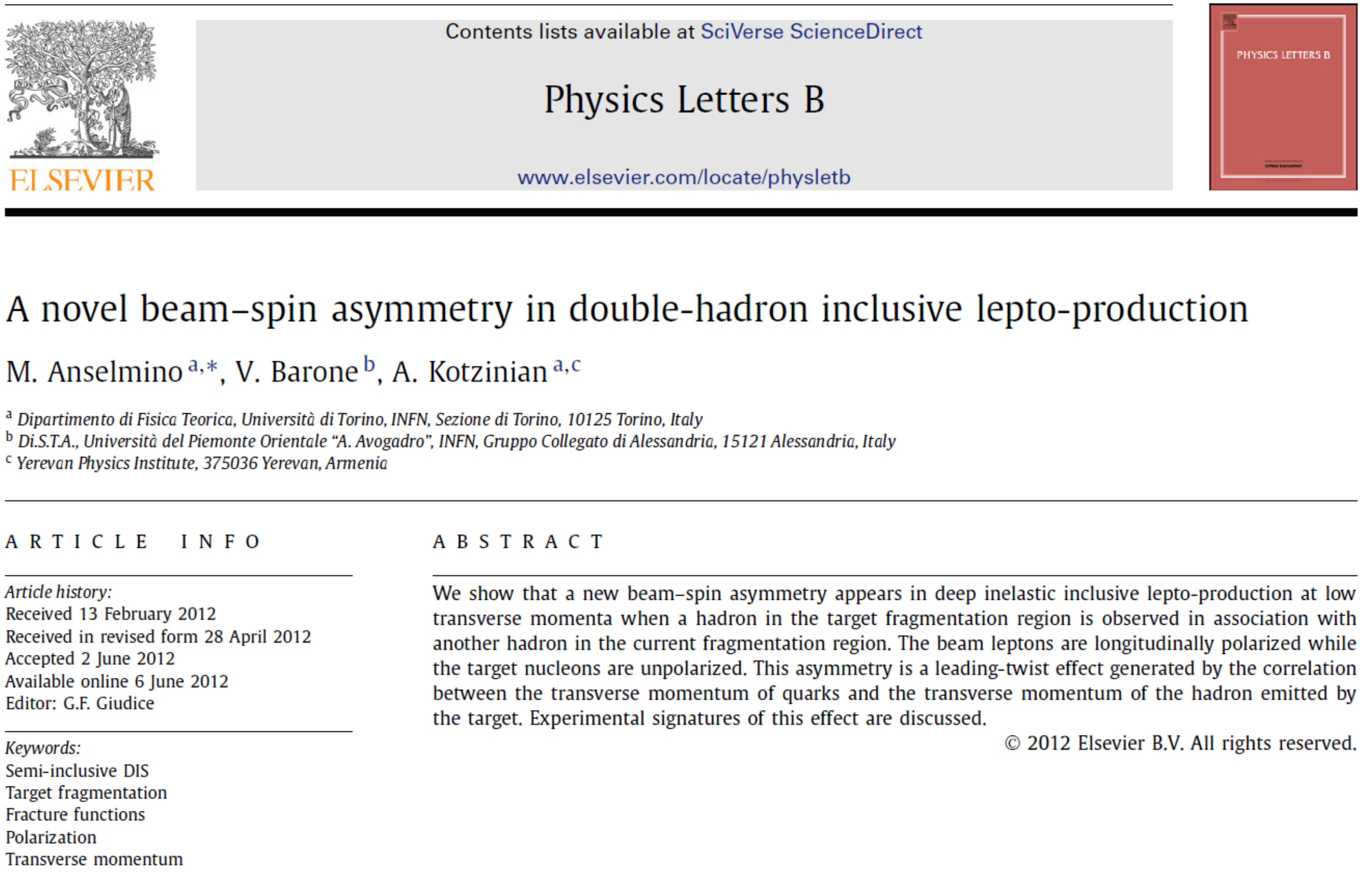
Di-hadron SIDIS: back2back configuration

- how the remnant system dresses itself up to become a full-fledged hadron?
- correlation with the spin of the target or/and the produced particles
- control the flavor content of the final state hadron in current fragmentation (detecting the target hadron)
- study correlations in target vs current and access factorization breaking effects (similar to pp case)
- access quark short-range correlations and χSB (*Schweitzer et al*)





Di-hadron SIDIS: back2back configuration



ELSEVIER

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

A novel beam–spin asymmetry in double-hadron inclusive lepto-production

M. Anselmino [a,*], V. Barone [b], A. Kotzinian [a,c]

[a] *Dipartimento di Fisica Teorica, Università di Torino, INFN, Sezione di Torino, 10125 Torino, Italy*
[b] *Di.S.T.A., Università del Piemonte Orientale "A. Avogadro", INFN, Gruppo Collegato di Alessandria, 15121 Alessandria, Italy*
[c] *Yerevan Physics Institute, 375036 Yerevan, Armenia*

ARTICLE INFO

Article history:
Received 13 February 2012
Received in revised form 28 April 2012
Accepted 2 June 2012
Available online 6 June 2012
Editor: G.F. Giudice

Keywords:
Semi-inclusive DIS
Target fragmentation
Fracture functions
Polarization
Transverse momentum

ABSTRACT

We show that a new beam–spin asymmetry appears in deep inelastic inclusive lepto-production at low transverse momenta when a hadron in the target fragmentation region is observed in association with another hadron in the current fragmentation region. The beam leptons are longitudinally polarized while the target nucleons are unpolarized. This asymmetry is a leading-twist effect generated by the correlation between the transverse momentum of quarks and the transverse momentum of the hadron emitted by the target. Experimental signatures of this effect are discussed.

Phys. Lett. B 713 (2012) 317

Di-hadron SIDIS: back2back configuration

$$\mathcal{F}_{LU}, \mathcal{F}_{UU} \propto \mathcal{C}[\mathcal{M}\mathcal{D}]$$

$$\begin{aligned}
&\frac{d\sigma^{l(\lambda_l)\, N \to l\, h_1 h_2\, X}}{dx_B\, dy\, dz_1\, d\zeta_2\, d\mathbf{P}_{1\perp}^2\, d\mathbf{P}_{2\perp}^2\, d\phi_1\, d\phi_2} \\
&= \frac{\pi \alpha_{\rm em}^2}{x_B y Q^2} \left\{ \left(1 - y + \frac{y^2}{2}\right) \mathcal{F}_{UU} \right. \\
&+ (1-y)\, \mathcal{F}_{UU}^{\cos(\phi_1+\phi_2)} \cos(\phi_1+\phi_2) \\
&+ (1-y)\, \mathcal{F}_{UU}^{\cos(2\phi_1)} \cos(2\phi_1) \\
&+ (1-y)\, \mathcal{F}_{UU}^{\cos(2\phi_2)} \cos(2\phi_2) \\
&- \left. \boxed{\lambda_l\, y \left(1 - \frac{y}{2}\right) \mathcal{F}_{LU}^{\sin(\phi_1-\phi_2)} \sin\Delta\phi} \right\} \\
&\equiv \sigma_{UU} + \lambda_l\, \sigma_{LU},
\end{aligned}$$

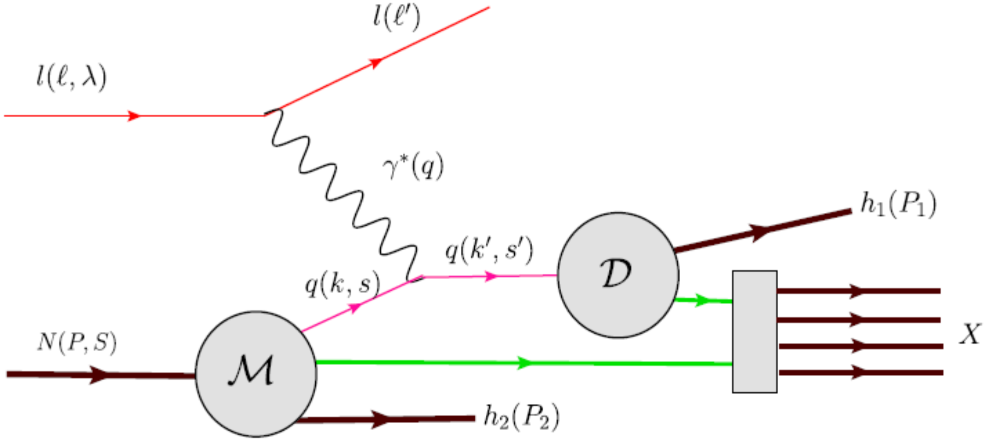
Fracture Functions:

probability of finding a parton i with fractional momentum x_B and a hadron h with fractional momentum ζ

$$\mathcal{M}(x_B, \zeta, k_\perp, P_{\perp 2})$$

Fragmentation Functions:

$$\mathcal{D}(z_1, k_\perp)$$

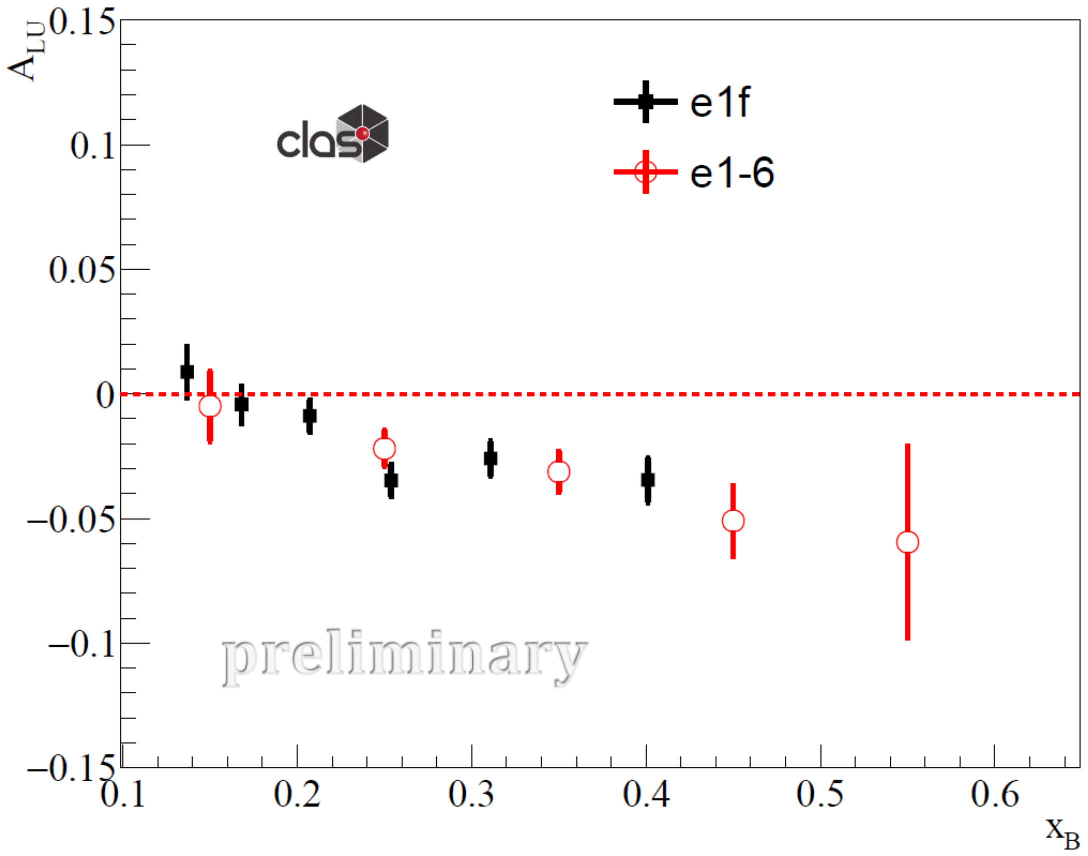


Back-to-back $ep \rightarrow ep\pi^+X$: x_B

- different target positions (- 4 cm or -25 cm)
- different torus magnetic field
- coverage extended to high Q^2

The measurements on the two hydrogen data sets can be combined

$$\mathcal{F}_{LU}^{\sin(\phi_1-\phi_2)} = \frac{|\boldsymbol{P}_{1\perp}||\boldsymbol{P}_{2\perp}|}{m_N m_2}\mathcal{C}[w_5 \hat{l}_1^{\perp h} D_1]$$

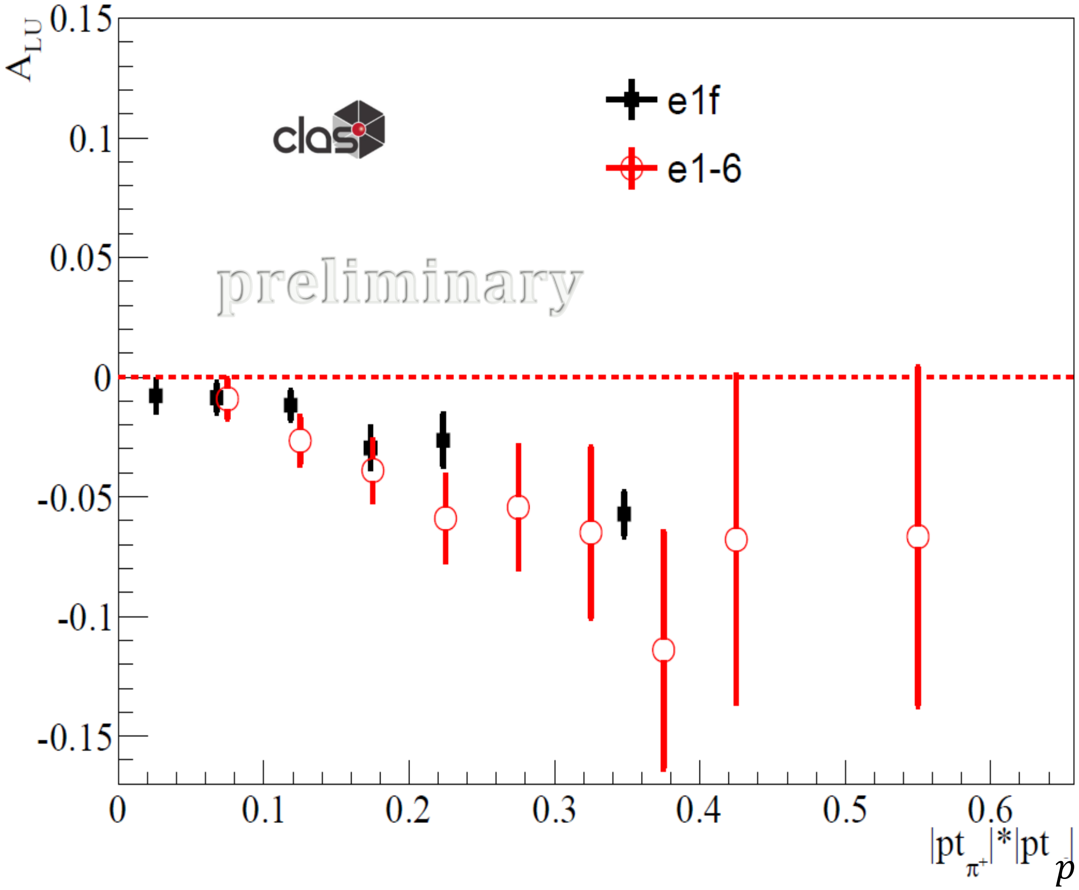


Back-to-back $ep \to ep\pi^+X$: $|p_{T1}||p_{T2}|$

- different target positions (- 4 cm or -25 cm)
- different torus magnetic field
- coverage extended to high Q^2

The measurements on the two hydrogen data sets can be combined

$$\mathcal{F}_{LU}^{\sin(\phi_1-\phi_2)} = \frac{|\boldsymbol{P}_{1\perp}||\boldsymbol{P}_{2\perp}|}{m_N m_2}\mathcal{C}[w_5 \hat{l}_1^{\perp h} D_1]$$

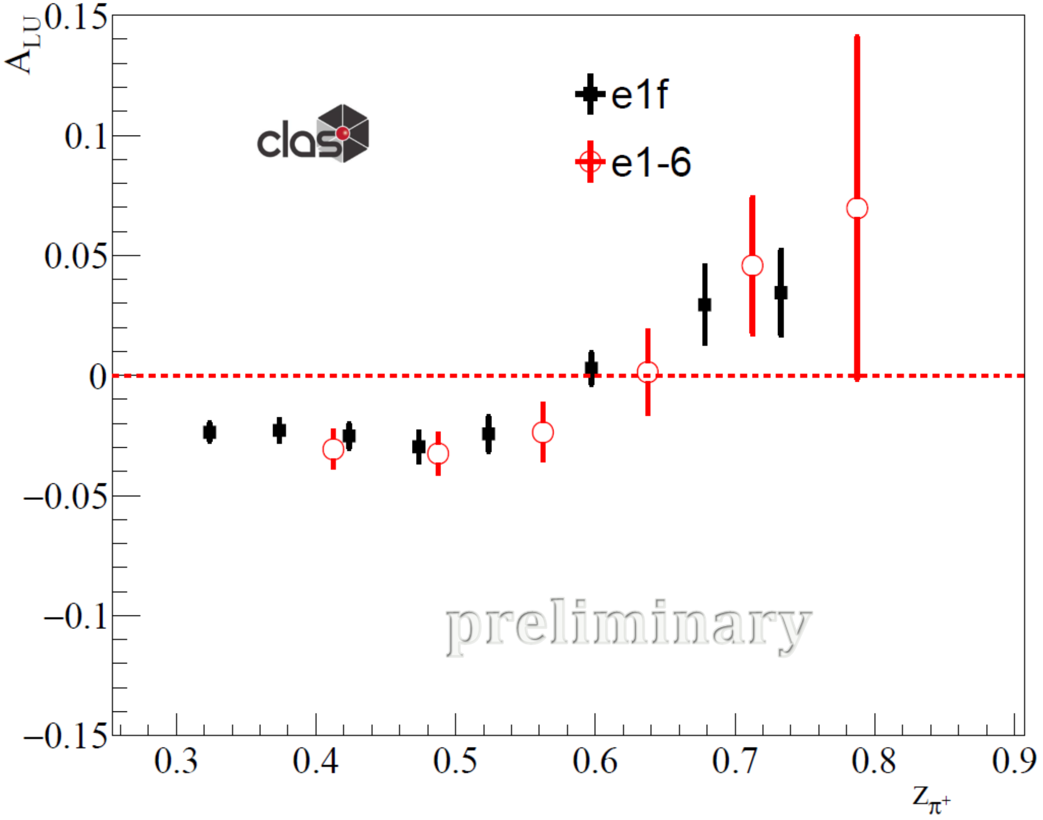


Back-to-back $ep \rightarrow ep\pi^+X$: z

- different target positions (- 4 cm or -25 cm)
- different torus magnetic field
- coverage extended to high Q^2

The measurements on the two hydrogen data sets can be combined

$$\mathcal{F}_{LU}^{\sin(\phi_1-\phi_2)} = \frac{|\boldsymbol{P}_{1\perp}||\boldsymbol{P}_{2\perp}|}{m_N m_2}\mathcal{C}[w_5 \hat{l}_1^{\perp h} \underbrace{D_1}_{\mathcal{D}(z)}]$$



z dependence common to single-hadron SIDIS → dictated by single-hadron Fragmentation Functions

Hall-B: Higher twist PDF $e(x)$ through 2h SIDIS

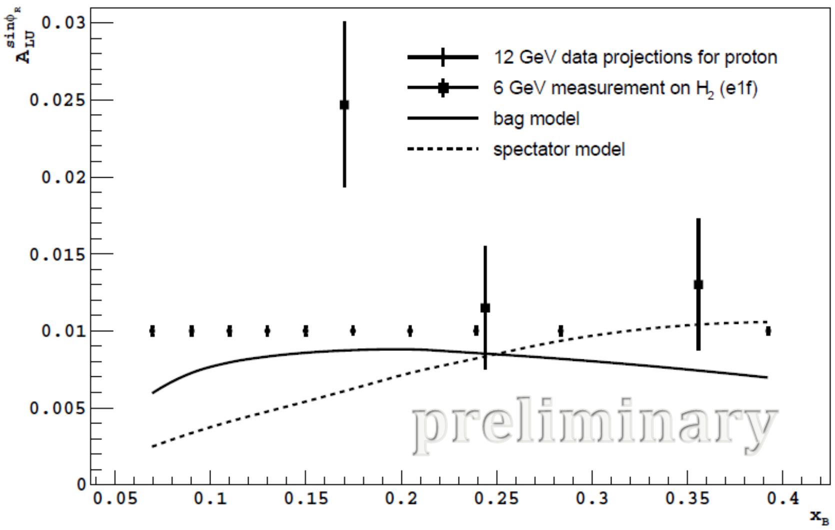
Twist-3 Physics

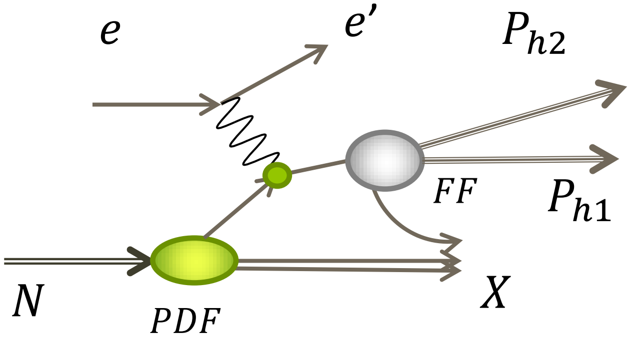
$e(x)$ → important information on the non-perturbative dynamics of the nucleon, e.g. quark-gluon correlations; nucleon **scalar charge**

$e(x)$ moments connected to the nucleon-pion sigma term

It appears in the di-hadron SIDIS Beam-Spin Asymmetry:

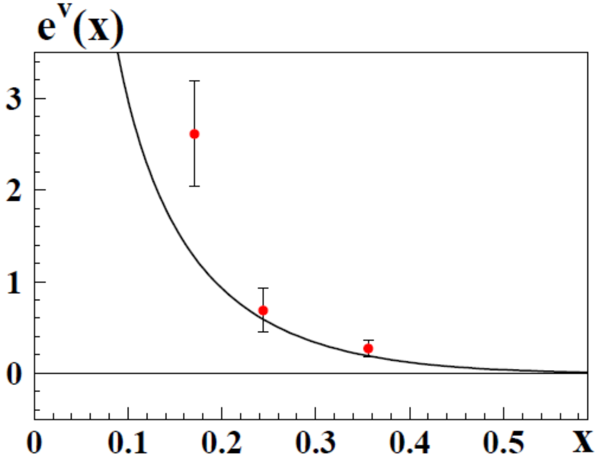
$$A_{LU} \propto F_{LU} = e(x) H_1^{\sphericalangle q} + f_1(x) \tilde{G}^{\sphericalangle q}$$





A. Courtoy, extraction on preliminary CLAS data - arXiv:1405.7659

LFCQM, Lorcé, Pasquini, Schweitzer, [JHEP01(2015)103] **arXiv:1411.2550**



Hall-B: Higher twist PDF $e(x)$ through 2h SIDIS

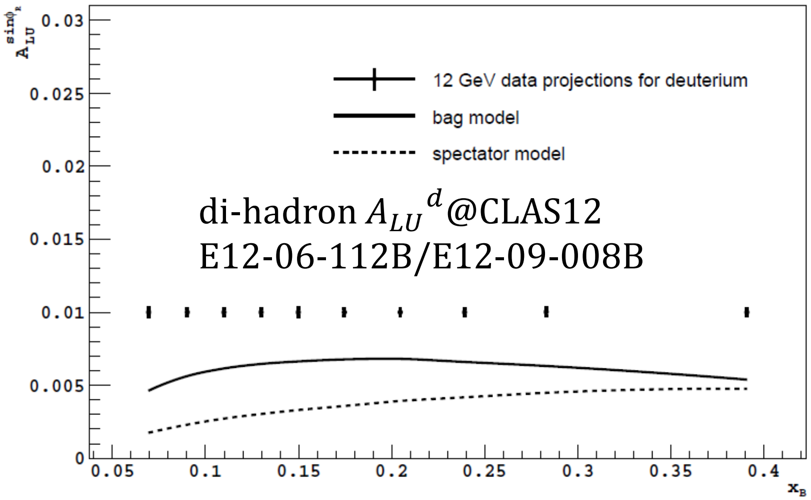
Twist-3 Physics

$e(x)$ → important information on the non-perturbative dynamics of the nucleon, e.g. quark-gluon correlations; nucleon **scalar charge**

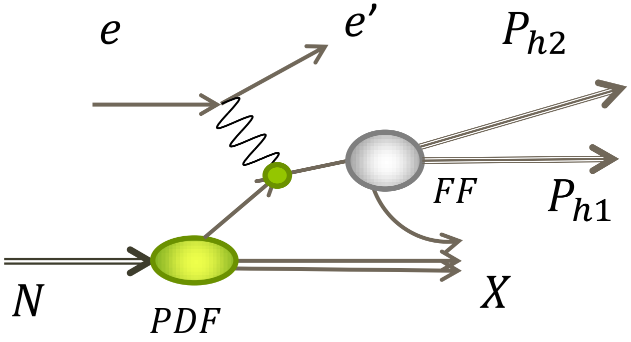
$e(x)$ moments connected to the nucleon-pion sigma term

It appears in the di-hadron SIDIS Beam-Spin Asymmetry:

$$A_{LU} \propto F_{LU} = e(x) H_1^{\sphericalangle q} + f_1(x) \tilde{G}^{\sphericalangle q}$$

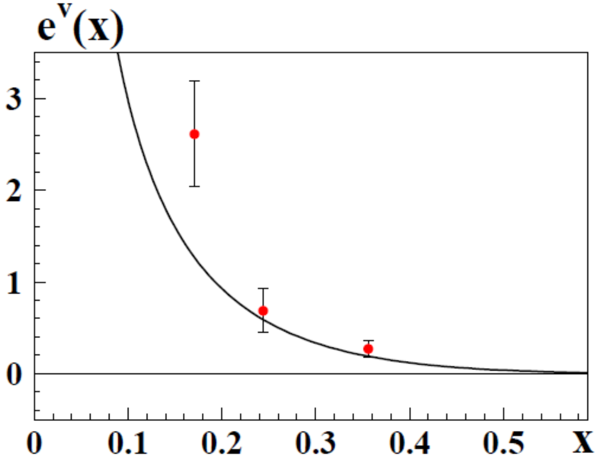


di-hadron $A_{LU}{}^{d}$@CLAS12
E12-06-112B/E12-09-008B



A. Courtoy, extraction on preliminary CLAS data - arXiv:1405.7659

LFCQM, Lorcé, Pasquini, Schweitzer,
JHEP01(2015)103
arXiv:1411.2550



Hall-B: Higher twist PDF $e(x)$ through 2h SIDIS

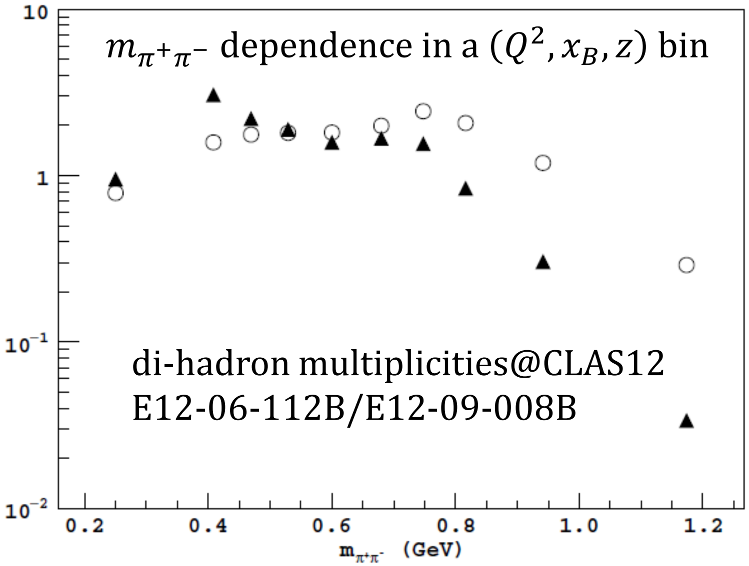
Twist-3 Physics

$e(x)$ → important information on the non-perturbative dynamics of the nucleon, e.g. quark-gluon correlations; nucleon **scalar charge**

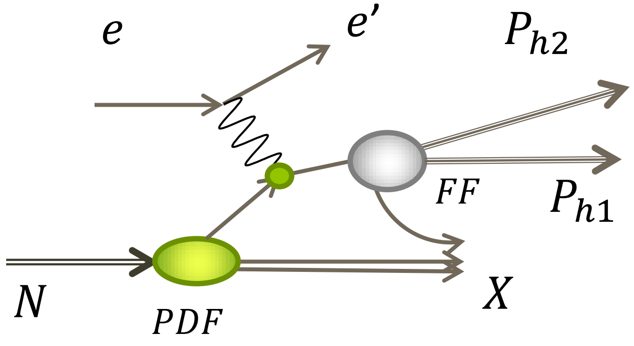
$e(x)$ moments connected to the nucleon-pion sigma term

It appears in the di-hadron SIDIS Beam-Spin Asymmetry:

$$A_{LU} \propto F_{LU} = e(x) H_1^{\sphericalangle q} + f_1(x) \tilde{G}^{\sphericalangle q}$$

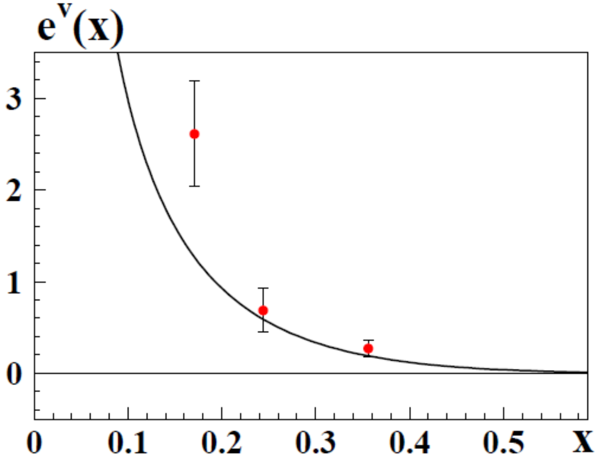

$m_{\pi^+\pi^-}$ dependence in a (Q^2, x_B, z) bin

di-hadron multiplicities@CLAS12
E12-06-112B/E12-09-008B



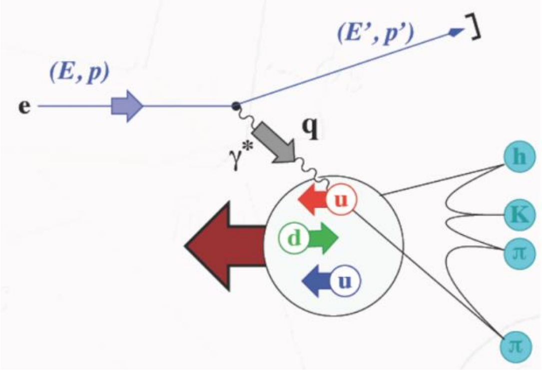
A. Courtoy, extraction on preliminary CLAS data - arXiv:1405.7659

LFCQM, Lorcé, Pasquini, Schweitzer, JHEP01(2015)103 arXiv:1411.2550



Transverse Momentum Distributions

through Semi-Inclusive Deep-Inelastic Scattering



Hall-B & Hall-C: SIDIS unpolarized cross-section & Fragmentation

T. Navasardyan et al. PRL 98, 22001 (2007)
R. Asaturyan et al. PRC 85, 015202 (2012)
M. Osipenko et al., PRD 80, 032004 (2009) , π^+ *SIDIS*
$\rightarrow F_{UU}^{\cos(\varphi)}, F_{UU}^{\cos(2\varphi)}$
E12-06-112 on H_2, E12–09–008 on H_2, D_2

Hall-B: Access to **longitudinal** structure functions

A_{LU} on H_2: H. Avakian *et al.* (π^+), PRD69: 112004 (2004), W. Gohn *et al.* ($\pi^{\pm 0}$), PRD89: 072014 (2014), *M. Aghasyan et al.* (π^0)*, Phys. Lett. B 704, 397 (2011)*
A_{UL}, A_1 on NH_3: H. Avakian *et al.*, PRL105: 262002 (2010)
A_{LU}, A_{UL}, A_{LL} on NH_3: S. Jawalkar, S. Koirala PhD. thesis
E12-07-107, E12-09-009 on NH_3, ND_3

Hall-A & Hall-B: Access to **transverse** structure functions

A_{UT} on ^3He: X. Qian *et al.*, PRL107: 072003 (2011),
A_{LT} on ^3He: J. Huang *et al.*, PRL108: 052001 (2012)
E12-11-111 on hydrogen

s-quark content of the nucleon

arXiv: 1404.7204$^3He(e, e'k)X$
E12-09-008/9, E12-09-017/18, E12-11-111

Conclusions

- Hall-B (CLAS)@JLab significantly contributed to the knowledge of the quark dynamics in the valence region

- New results on longitudinally polarized observables

- Fully differential extraction of Multiplicities, $\cos\varphi$ and $\cos 2\varphi$ modulations performed with high accuracy, the latters exhibiting flavor dependence

- New phenomena connected to $q\bar{q}$ correlations inside the nucleon are being explored → significant A_{LU} in b2b measured in Hall-B@JLab for the first time in the pion-proton channel

- non-zero ${A_{UL}}^{\sin\varphi}$ is measured for neutral pions with high precision → A_{UL} maybe generated through the Sivers mechanism

- small ${A_{UL}}^{\sin 2\varphi}$ consistent with expectations of strong suppression of Collins effect for neutral pions, due to cancellation of roughly equal favored and unfavored Collins functions.

- **All the measurements will be significantly extended and improved in precision during the 12-GeV era**

backup

Azimuthal distributions in SIDIS

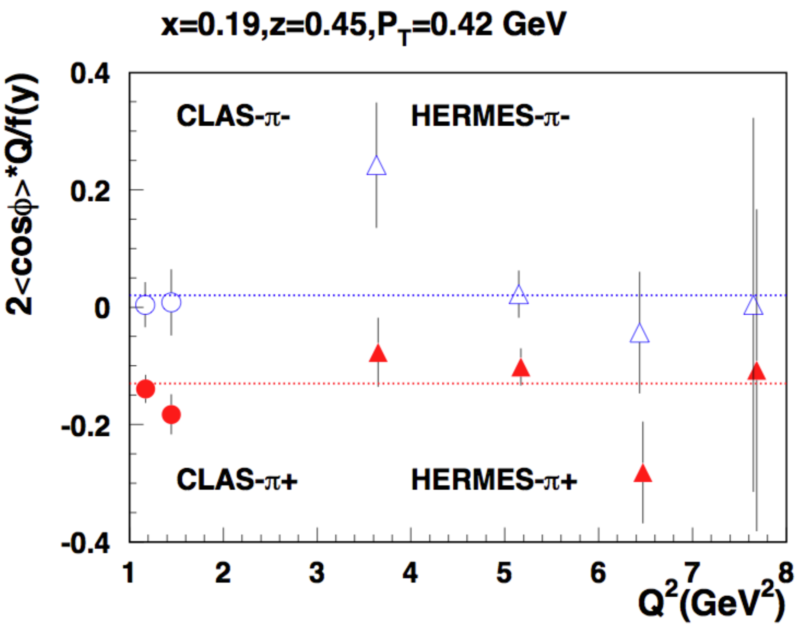
$f_1 \otimes D_1$

$$\frac{d^5\sigma}{dx\;dQ^2\;dz\;d\phi_h\;dP_{h\perp}^2} = \frac{2\pi}{2(k\cdot P)x}\,\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\{F_{UU,T}+\varepsilon F_{UU,L} + \sqrt{2\varepsilon\,(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos\left(2\phi_h\right) F_{UU}^{\cos 2\phi_h}\}$$

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

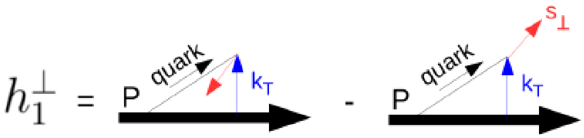
f_1 : unpolarized quark inside an unpolarized nucleon →it quantifies spin-orbit correlations, thus requiring non-zero orbital angular momentum

$h_1{}^{\perp}$: transversely-polarized quark inside an unpolarized nucleon

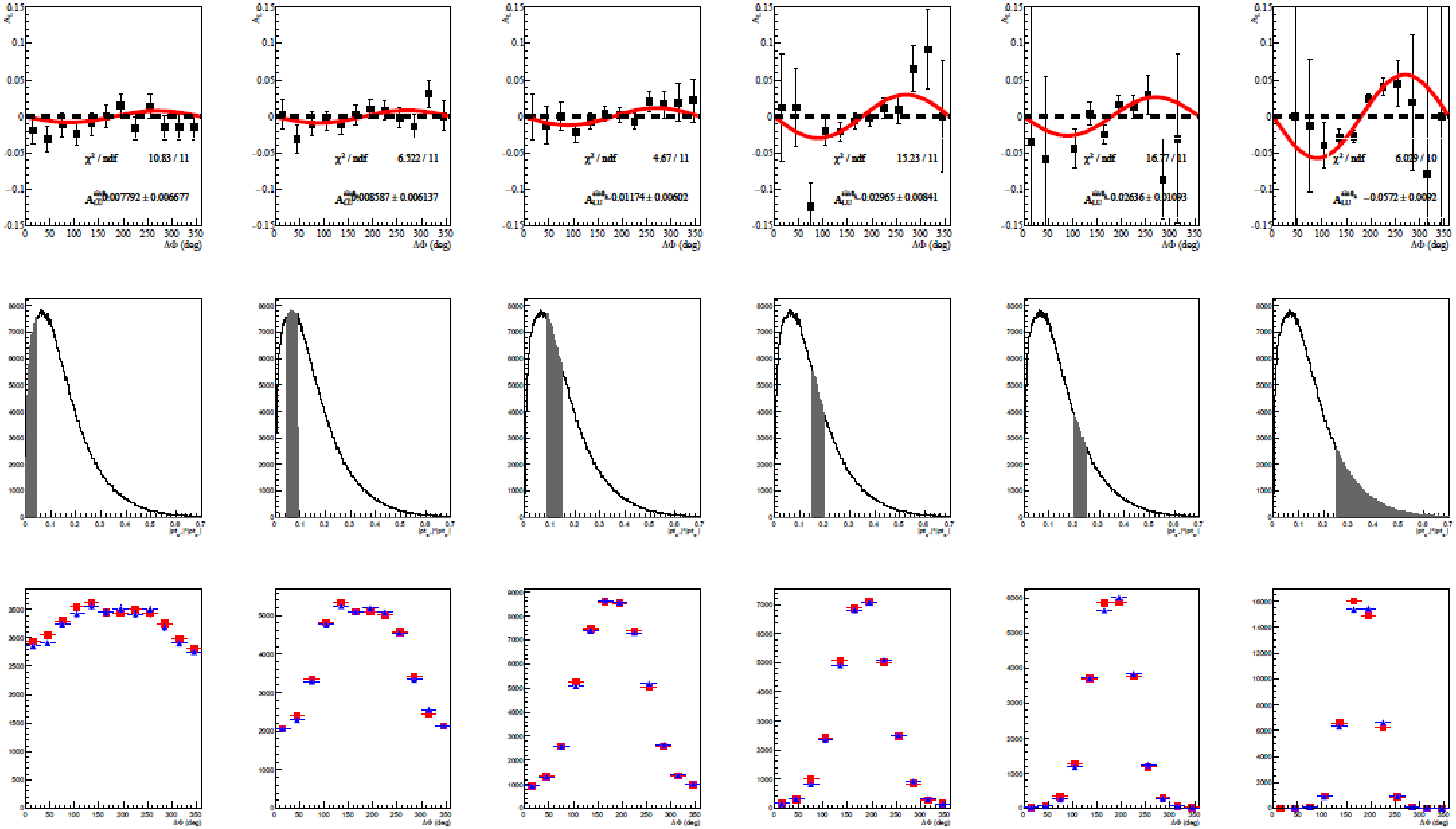


N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

Boer-Mulder function



Back-to-back pion and proton: $|p_{T1}||p_{T2}|$distribution



Comparison with previous CLAS data

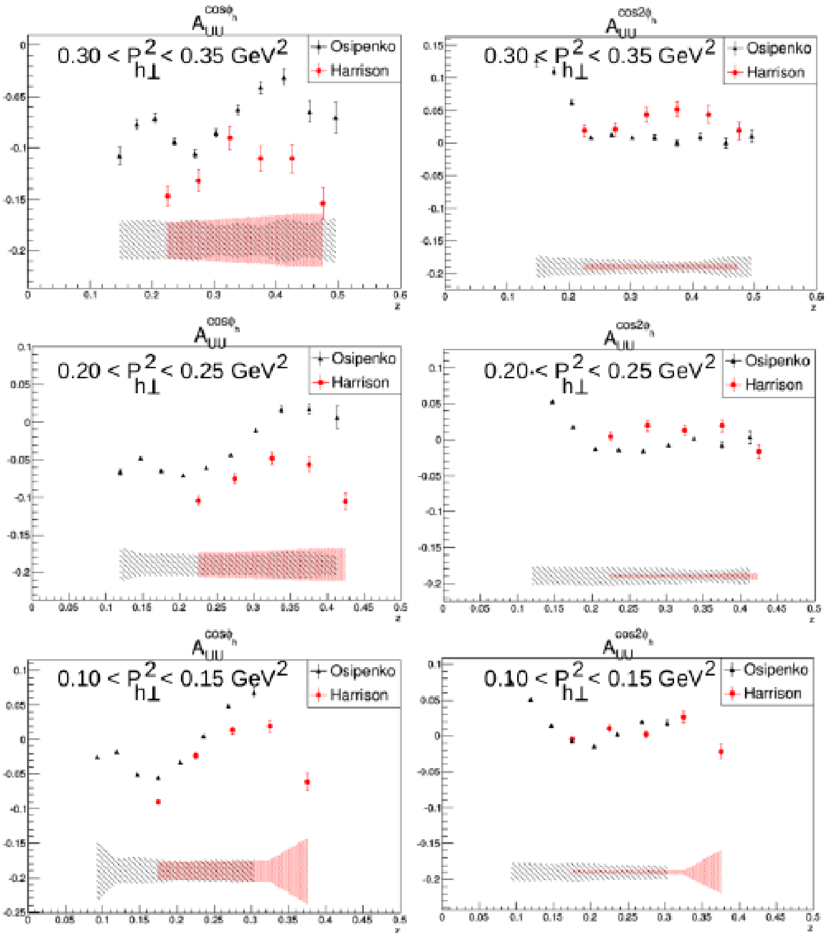
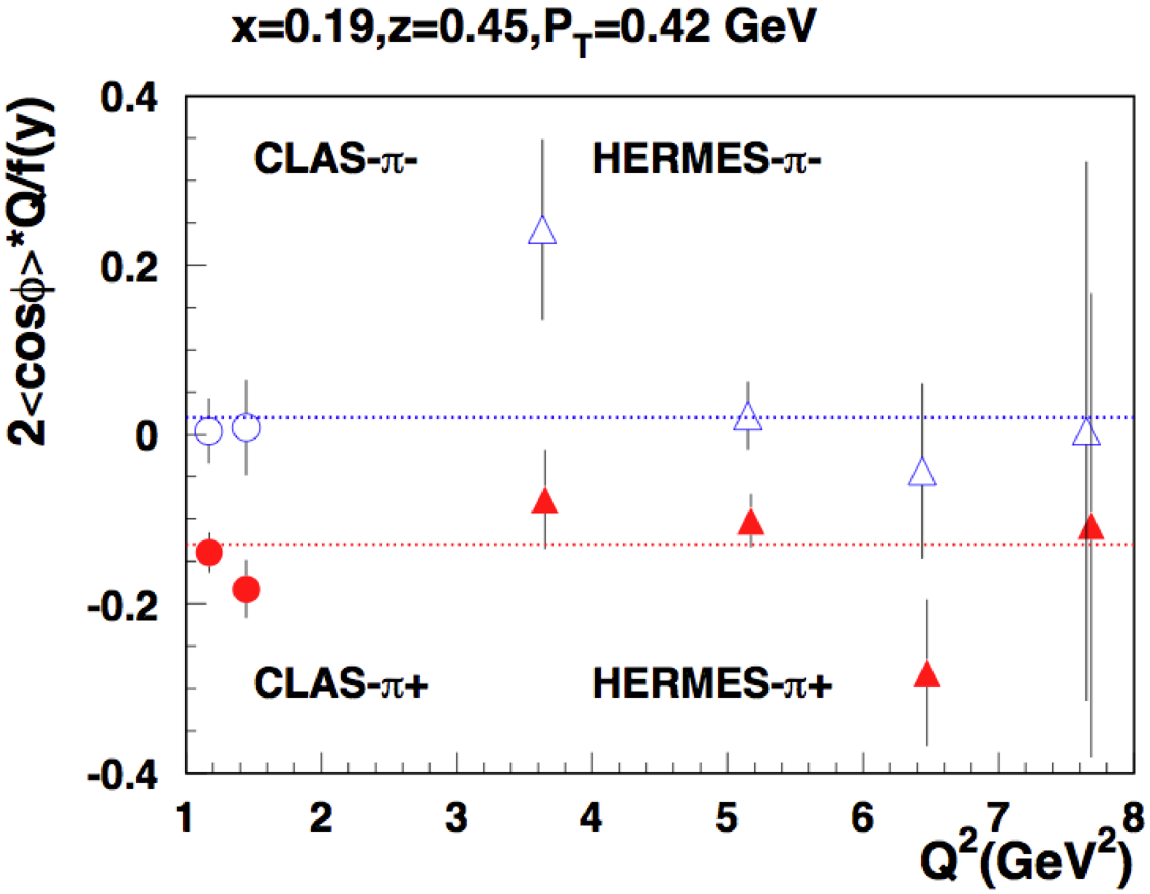


Fig. 6.1: A comparison between π^+ results in this analysis and a previous CLAS analysis. The x-Q^2 bin here is the high Q^2 bin for $0.2 < x < 0.3$.

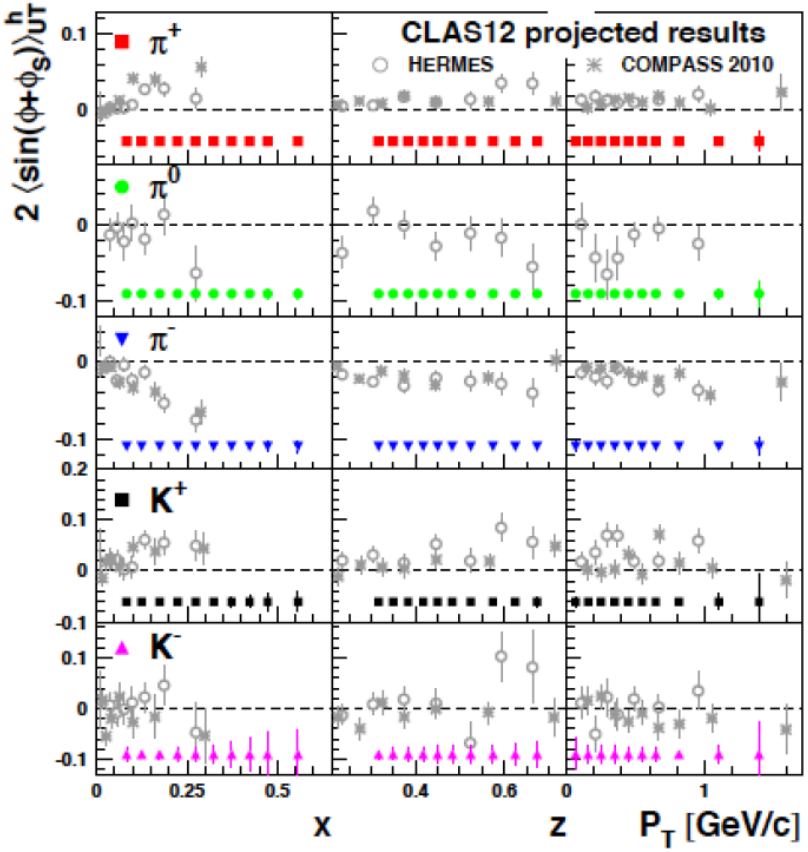
M. Osipenko *et al.*, Phys. Rev. D80 032004 (2009).

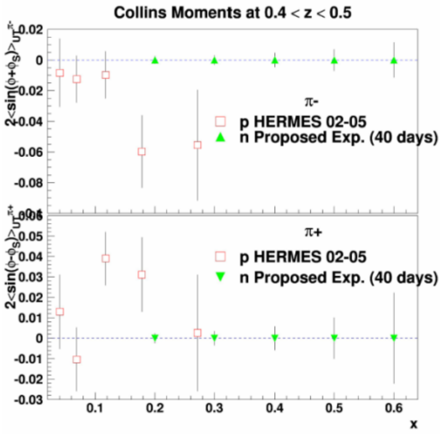
Comparison with HERMES data

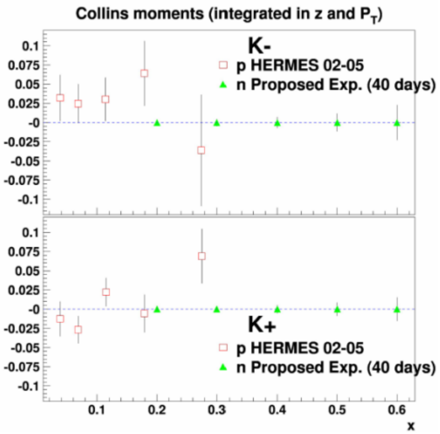


h_1 through 1h SIDIS (Collins effect)

Hall-A@12 GeV: Collins effect on neutron
Hall-B@12 GeV: Collins effect on proton

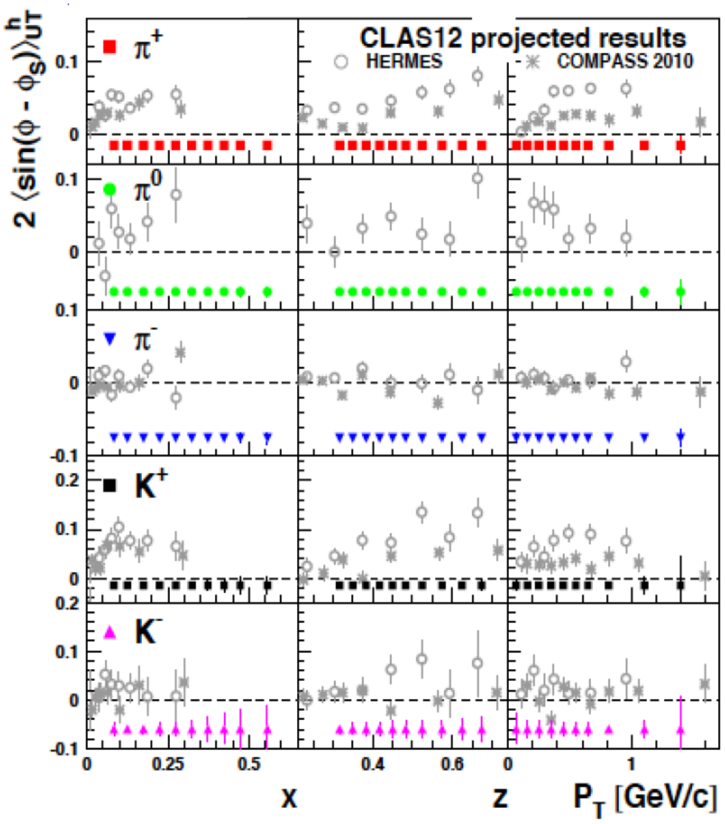


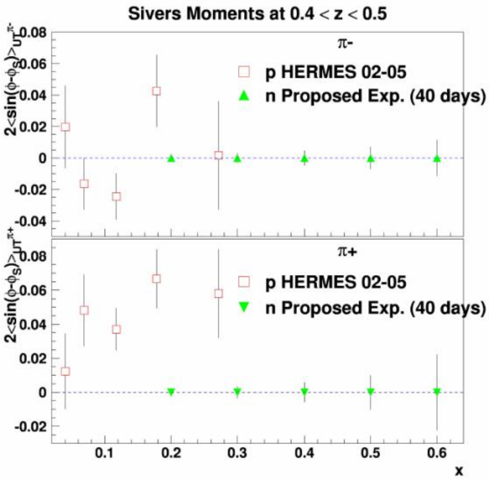


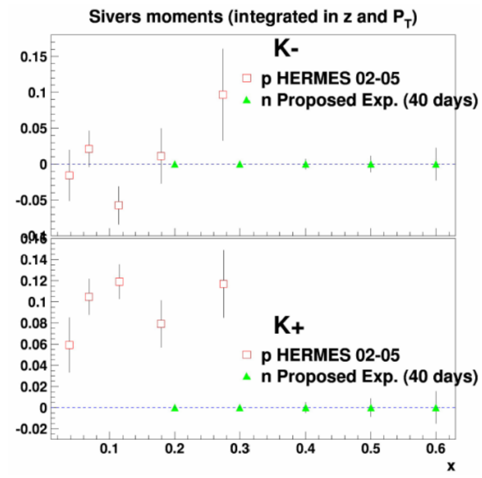


Sivers effect at 12 GeV

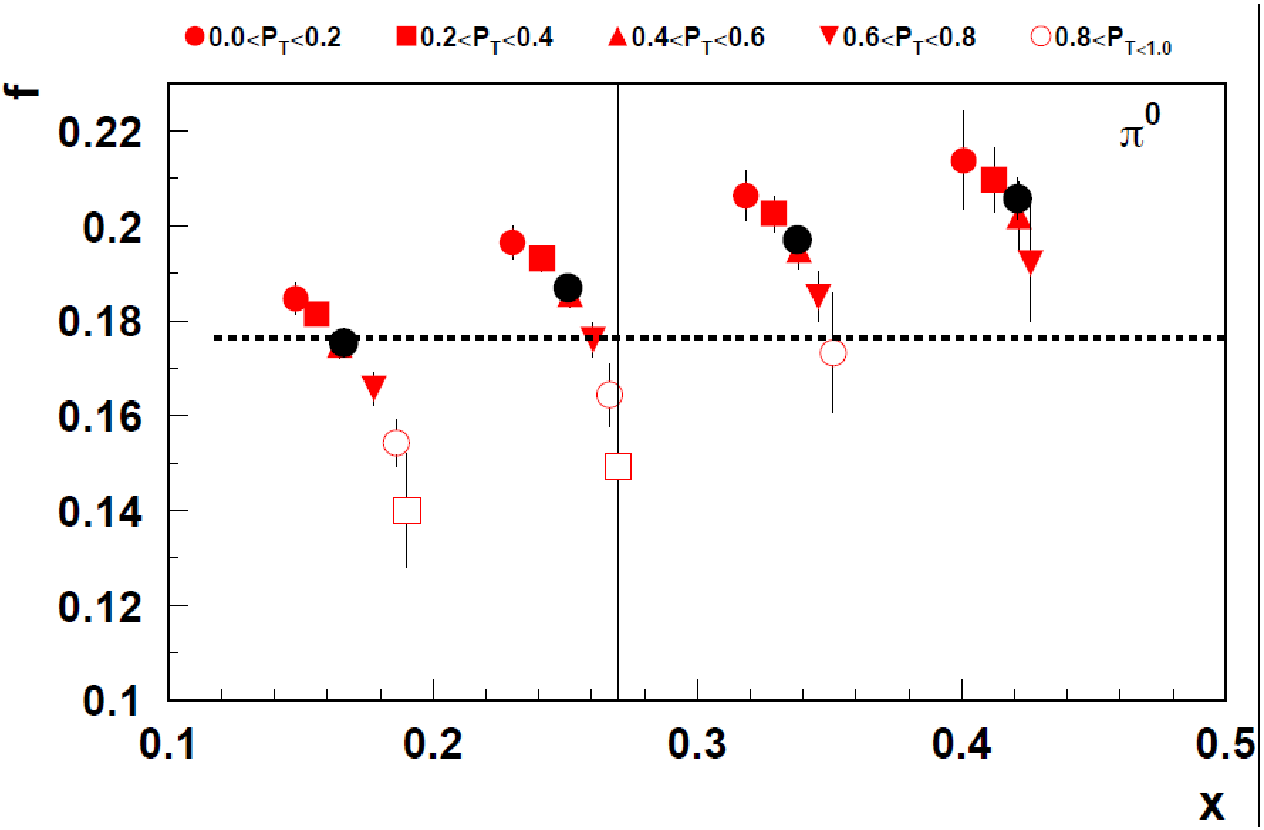
Hall-A@12 GeV: Sivers effect on neutron
Hall-B@12 GeV: Sivers effect on proton







Dilution factor



Useful relations

$$F_{UU,T} = \mathcal{C}\left[f_1 D_1\right],$$

$$F_{UU,L} = 0,$$

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{p}_T}{M_h}\left(xhH_1^{\perp} + \frac{M_h}{M}f_1\frac{\tilde{D}^{\perp}}{z}\right) - \frac{\hat{\mathbf{h}}\cdot\mathbf{k}_T}{M}\left(xf^{\perp}D_1 + \frac{M_h}{M}h_1^{\perp}\frac{\tilde{H}}{z}\right)\right]$$

$$F_{UU}^{\cos 2\phi_h} = \mathcal{C}\left[-\frac{2(\hat{\mathbf{h}}\cdot\mathbf{p}_T)(\hat{\mathbf{h}}\cdot\mathbf{k}_T) - \mathbf{p}_T\cdot\mathbf{k}_T}{MM_h}h_1^{\perp}H_1^{\perp}\right].$$

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