

# Study of the nucleon structure at CLAS and CLAS12

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# The nucleon picture

The picture of the nucleon changes with the energy of the photon.

Higher  $Q^2 \Rightarrow$  higher resolution

1. Elastic scattering: the intact proton recoils  $\rightarrow F_1(Q^2), F_2(Q^2)$
2. Resonance region
3. Valence quark
4. Sea quark and gluons
5. ...?

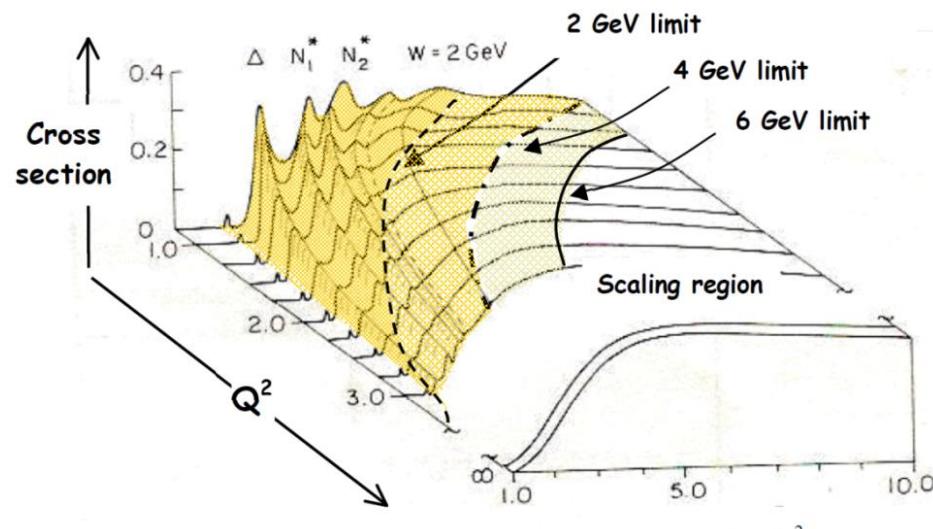
$Q^2$

*How do we relate the observed hadrons and their properties to the QCD Lagrangian degrees of freedom?*

CLAS domain

$$x = \frac{p}{P}$$

$W: \gamma^* - p$  invariant mass



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

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

# How do we model the nucleon?

1D picture of the nucleon: Parton Distribution Functions (PDFs),  $f(x)$  → Deep-Inelastic Scattering

1. PDFs's limit  $x \rightarrow 1$  still unknown (drop of cross-sections, high luminosity needed)
2. plenty of data on proton, poorer on neutron (lack of free neutron targets)
3. spin proton puzzle,  $s$ -quark content

Extension to a 3D picture:  $T(x, k_\perp), G(x, b_\perp) \rightarrow$   
Semi-Inclusive and Exclusive deep processes

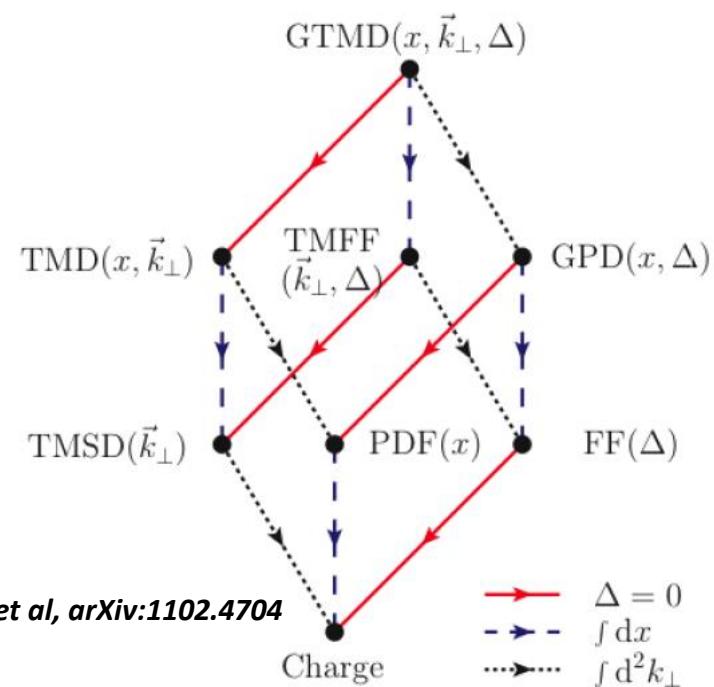
→ full mapping of the partons in coordinate and momentum space

→ access to quark Orbital Angular Momentum

*see S. Liuti's talk*

twist-2	$f_1(x)$	$g_1(x)$	$h_1(x)$
twist-3	$e(x)$	$h_L(x)$	$g_T(x)$

$g_1(x), h_1(x), e(x) \rightarrow$  related to nucleon axial, tensor and scalar charges respectively, can be connected to Lattice-QCD predictions



# 1D picture: duality & active degrees of freedom



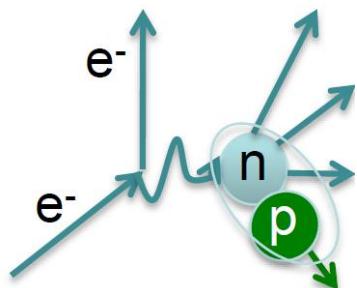
At what energy the partonic picture appears?

→ quark-hadron duality

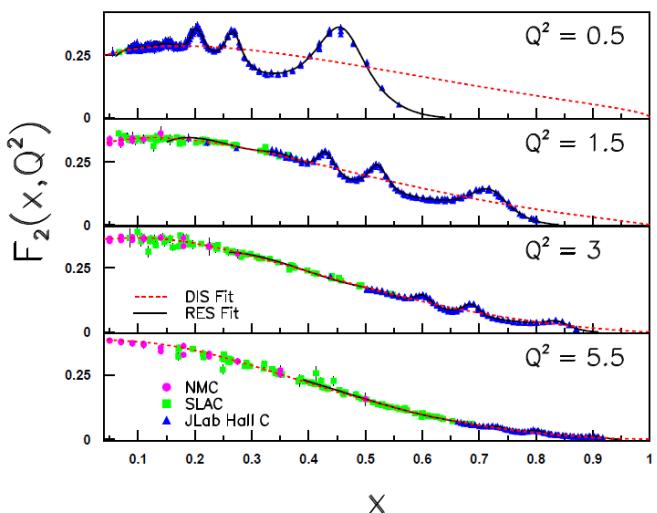
$$\frac{d^2\sigma_{DIS}}{dE'd\Omega} \propto c_1 F_1(x, Q^2) + c_2 F_2(x, Q^2)$$

$$F_2 = \sum_{q=1}^{N_f} e_q^2 f_q(x)$$

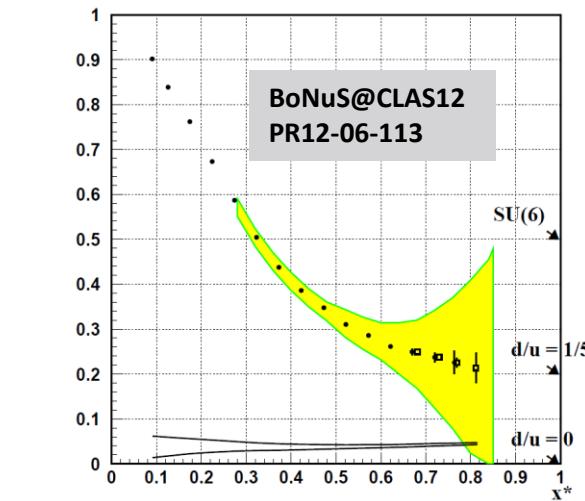
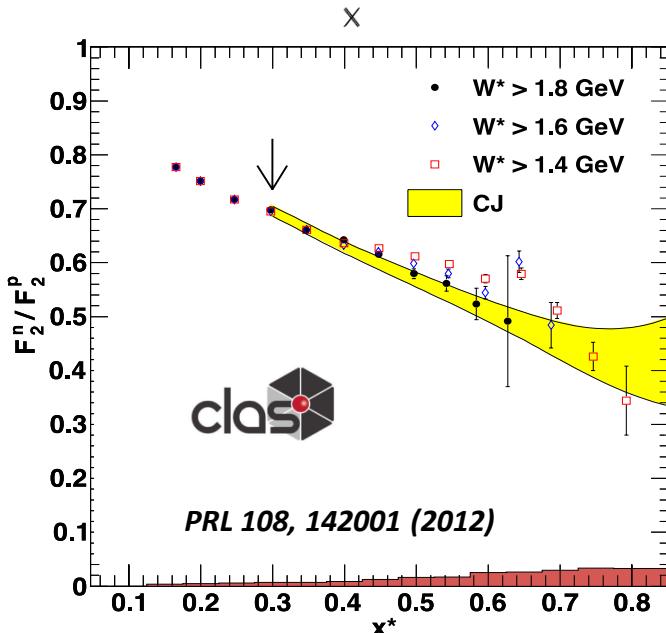
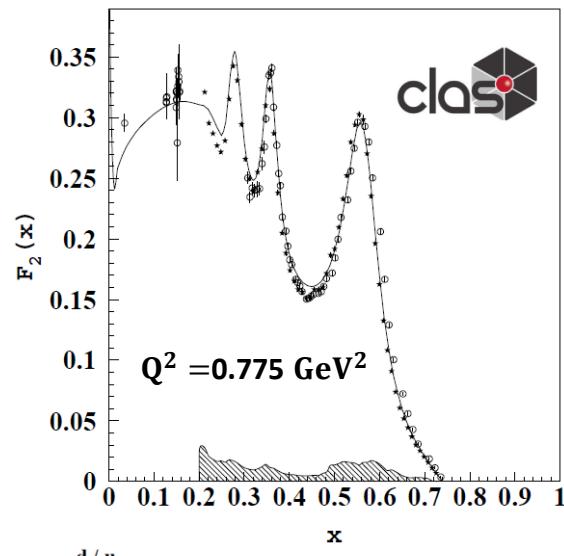
$F^p_2$  well known,  $F^n_2$  difficult to access → lack of free neutron target



BoNuS



Osipenko et al, Phys. Rev. D 67, 092001 (2003)



# 1D picture: helicity distributions and OAM

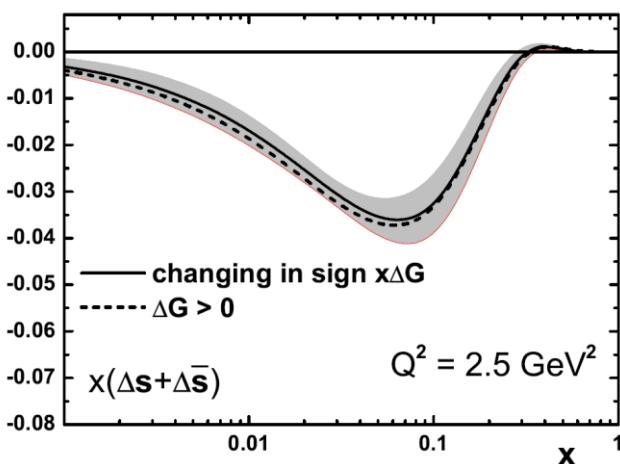


$g_1$ : connected to the axial charge

$\Delta u, \Delta d \rightarrow$  smaller contribution than expected to the proton spin

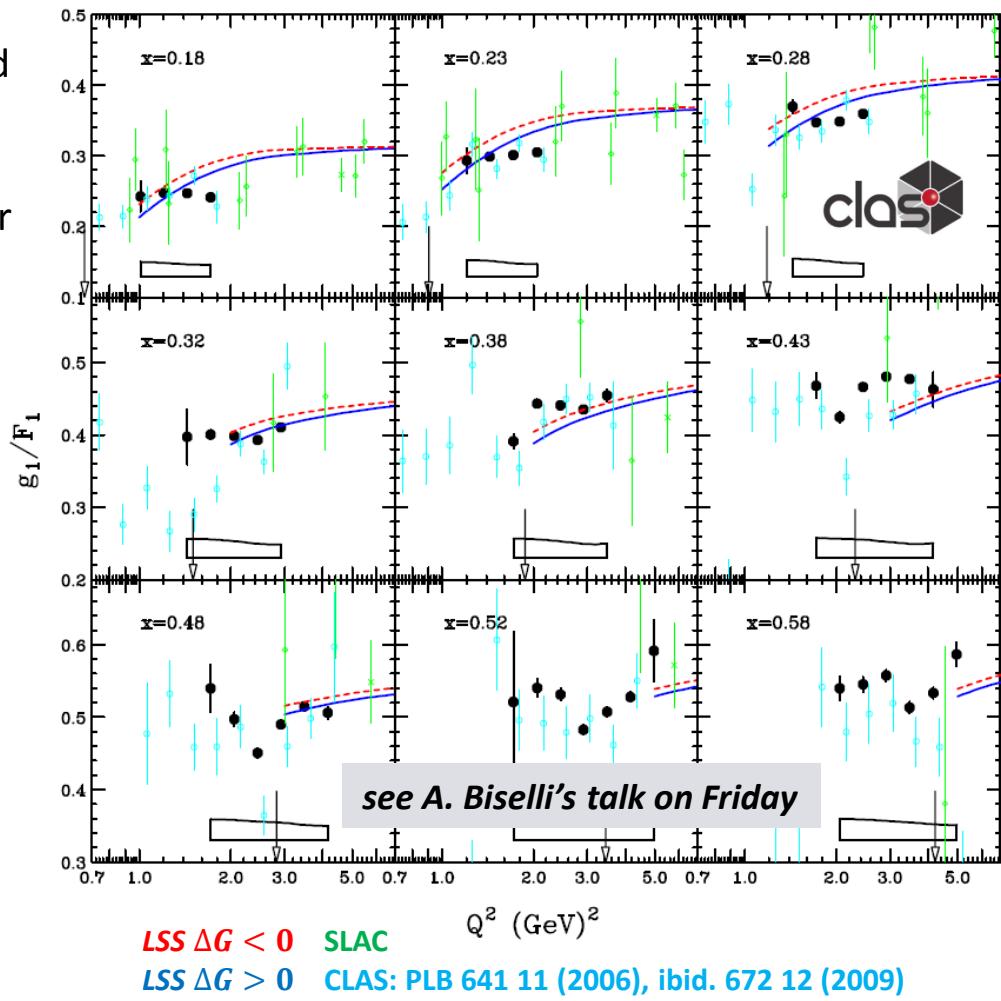
$\Delta G$ , strange quark and parton Orbital Angular Momentum must be sizeable

→ High precision extraction of  $g_1(x)$ , check of  $Q^2$  dependence ( $\Delta G$ , higher-twist terms)



Leader, Sidorov, Stamenov, arXiv:1410.1657

Y. Prok, Phys. Rev. C 90, 025212 (2014)



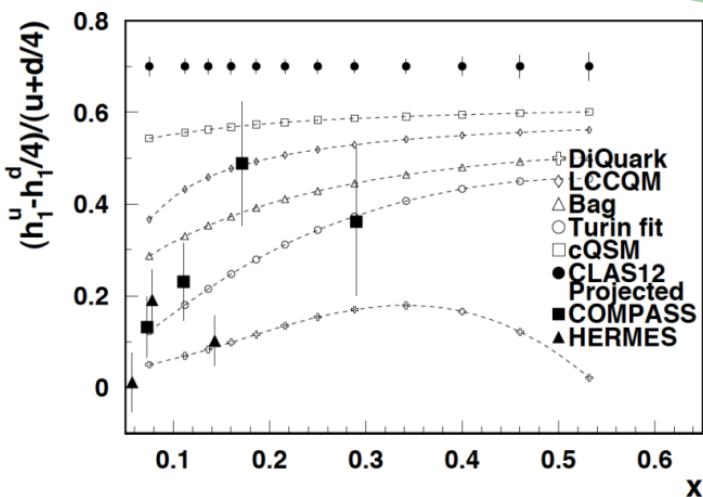
# 1D picture: transversity

$h_1^q(x, Q^2)$  is a *chiral-odd* PDF: not accessible through inclusive DIS → another *chiral-odd* object needed

**Single-hadron SIDIS:**  $h_1^q \otimes H_1^{\perp q} \rightarrow h_1^q(x, k_\perp, Q^2)$  *see M. E. Boglione's talk*

**Di-hadron SIDIS:**  $A_{UT} \propto h_1^q \cdot H_1^{\times q} \rightarrow h_1^q(x, Q^2)$

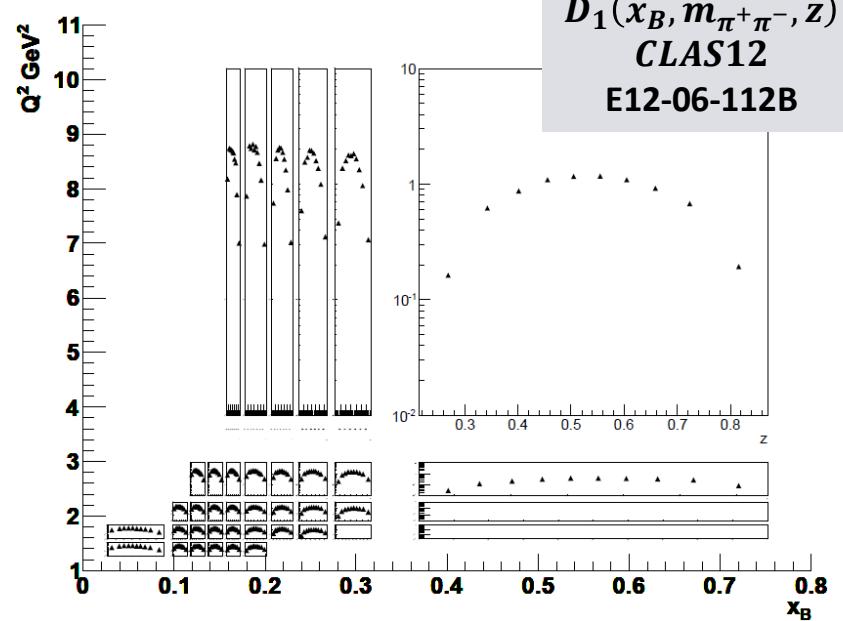
$$A_{UT} \propto \frac{h_1^q \cdot H_1^{\times q}}{f_1^q \cdot D_1^q} \xrightarrow{\text{extracted through Belle data}}$$



→ Complementary measurements on p and n in Hall-A (by SoLID) & Hall-B (C12-12-009)

## Tensor charge

- nucleon behaviour in possible tensorial interactions
- neutron beta decay



# 1D PDFs: nucleon structure@higher-twist



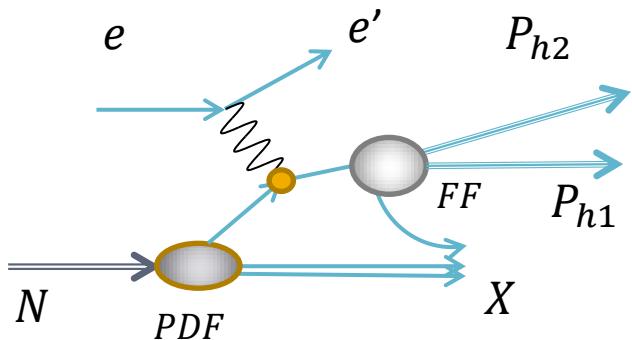
## Twist-3 Physics

$e(x) \rightarrow$  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

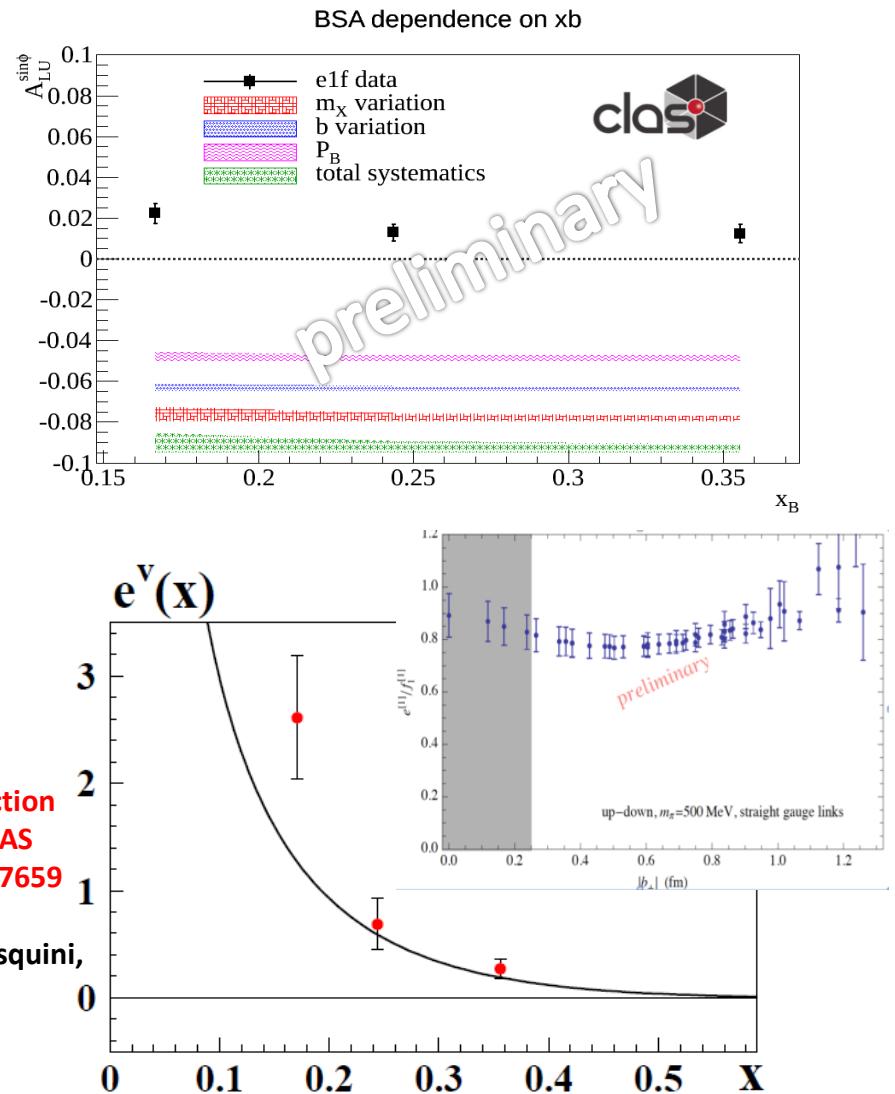
It appears in the di-hadron SIDIS Beam-Spin Asymmetry:

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



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

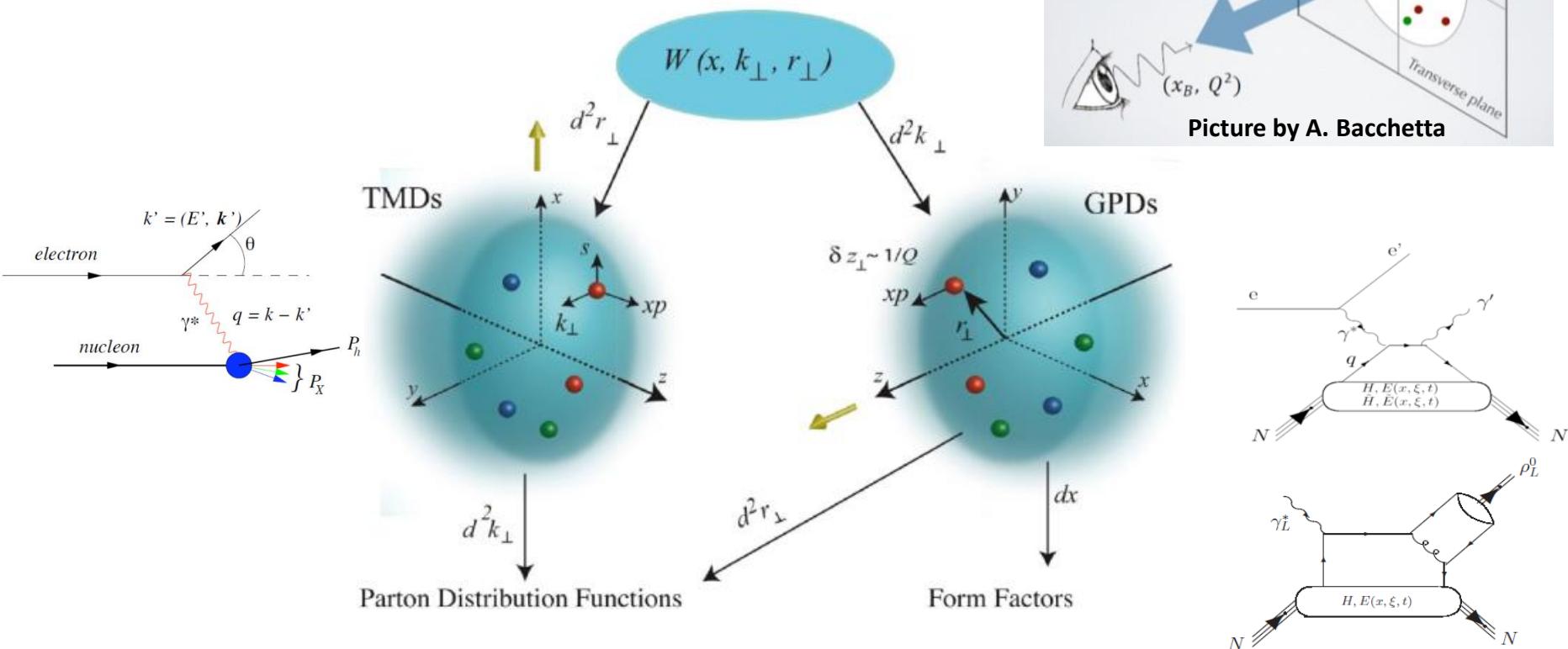
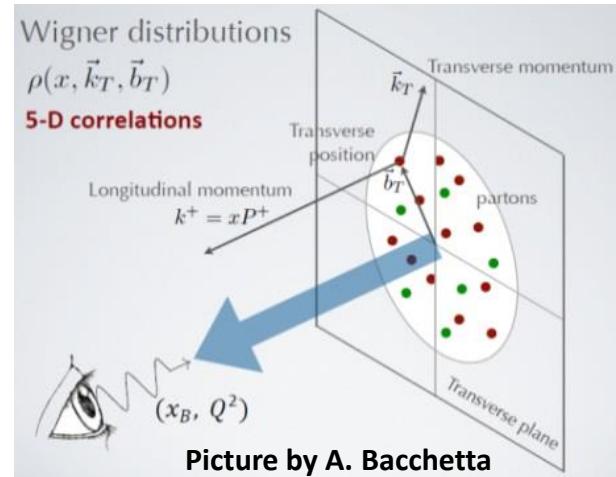
LFCQM, Lorcé, Pasquini, Schweitzer, arXiv:1411.2550



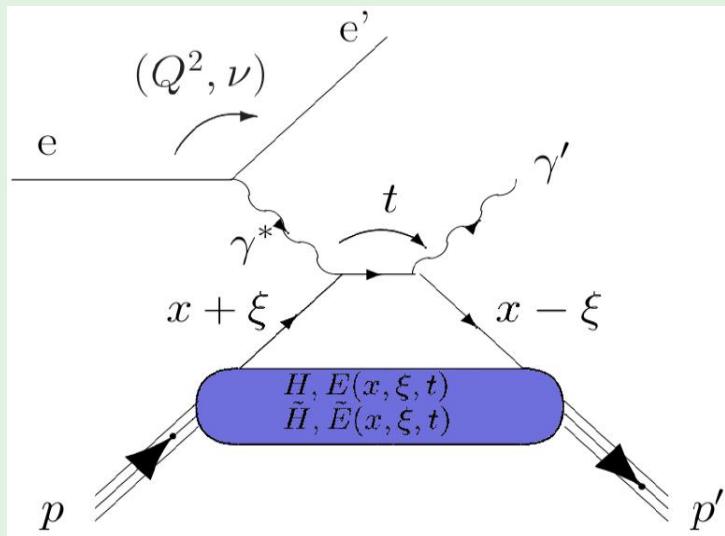
# 5D mapping of the nucleon

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

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

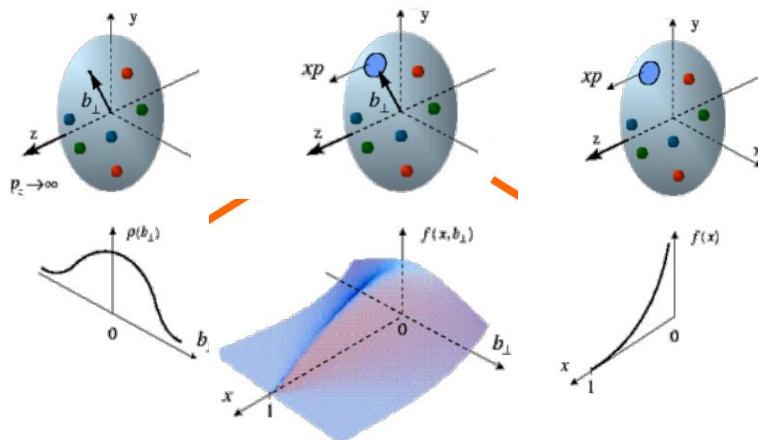


# Generalized Parton Distributions through DVCS & DVMP



1+2D description of the nucleon structure

Correlations among longitudinal momenta and transverse positions

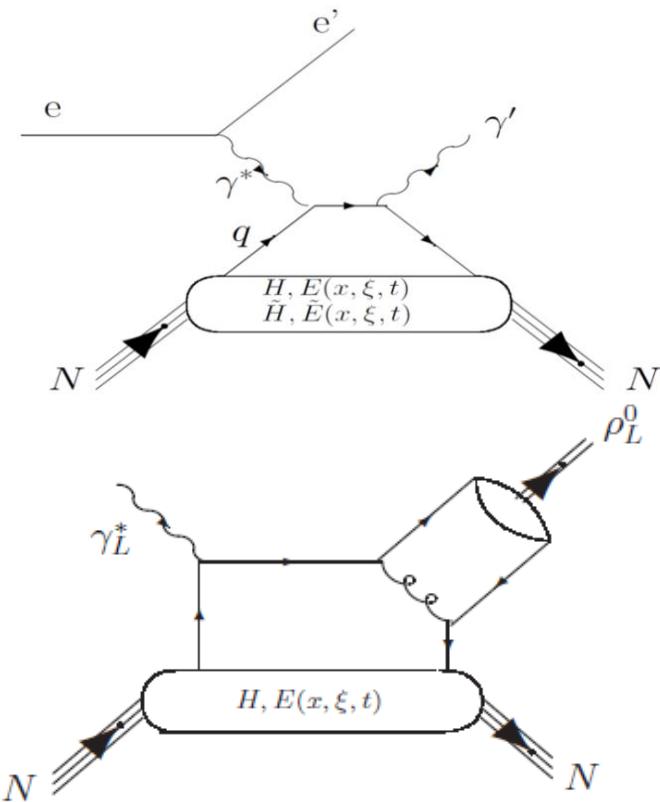


Connection to (quark) Orbital Angular Momentum

# 1+2D nucleon structure: Generalized Parton Distributions



**Generalized Parton Distributions** → transverse spatial images of quarks and gluons as a function of their longitudinal momentum fraction



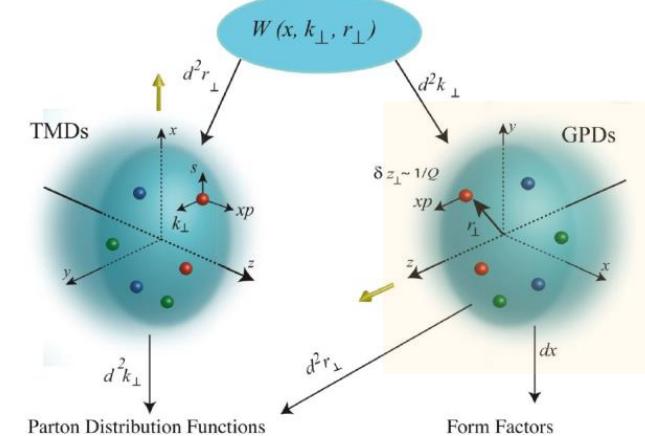
$$Q^2 = -(e - e')^2$$

$$x_B = \frac{Q^2}{2mv}$$

$$t = (p - p')^2$$

$$\xi \approx \frac{x_B}{2 - x_B}$$

$$v = E_e - E_{e'}$$



Handbag factorization valid in the Bjorken regime: high  $Q^2$ ,  $v$  at fixed  $x_B$ ,  $-t \ll Q^2$

4 chiral-even & 4 chiral-odd GPDs for each quark-flavor

DVMP&chiral-odd GPDs → see A. Biselli's talk on Friday

$$J_q = \frac{1}{2} \int_{-1}^{+1} dx x [H^q(x, \xi, t=0) + E^q(x, \xi, t=0)]$$

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# Sensitivity to GPDs in observables - Compton Form Factors



Only  $(\xi, t)$  are experimentally accessible, not  $x$ . GPDs will enter in the observables through

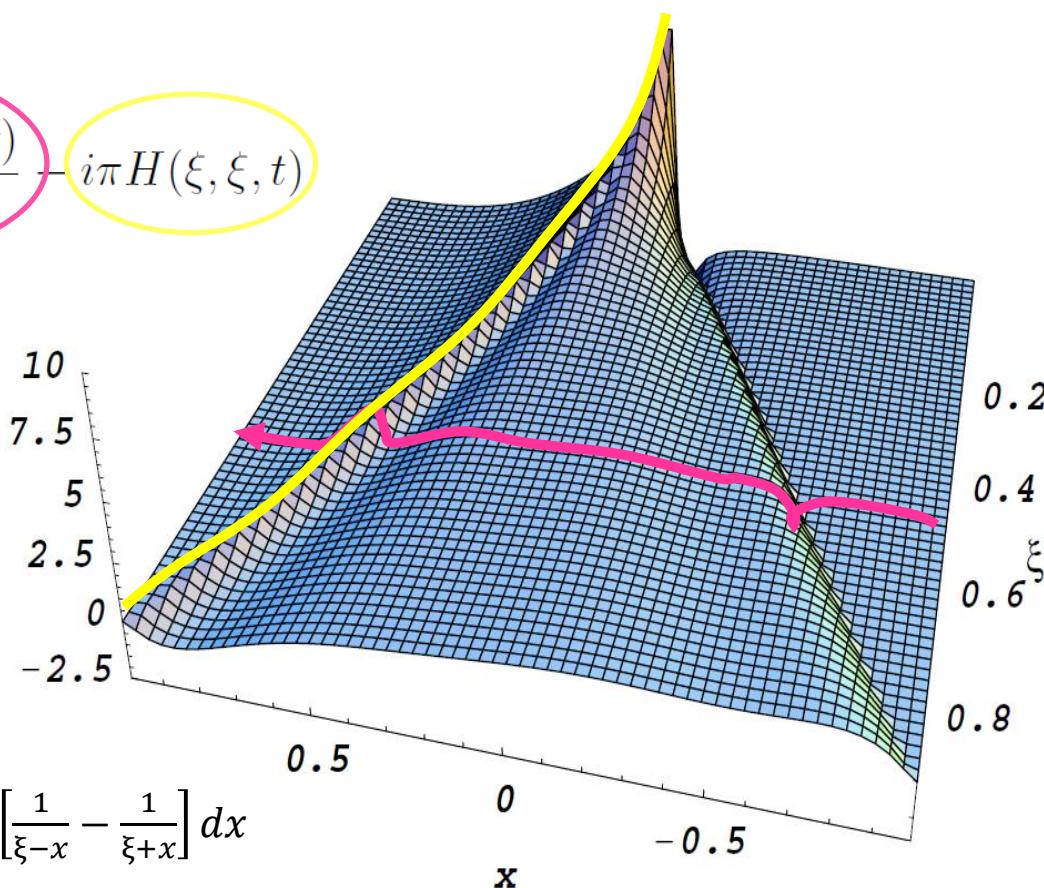
$$\int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi + i\epsilon} = \mathcal{P} \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi} + i\pi H(\xi, \xi, t)$$

The two parts will be accessible through observables sensible to the *imaginary* ( $A_{LU}, A_{UL}$ ) or the *real part* ( $A_{LL}, A_{BeamCharge}$ ) of the amplitude.

The following **Compton Form Factors** are introduced (experimentally observable):

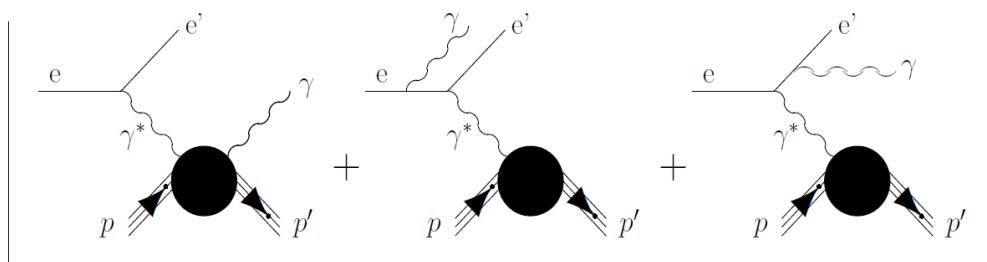
$$Re \mathcal{H}_q = e^2 q P \int_0^1 (H^q(x, \xi, t) - H^q(-x, \xi, t)) \left[ \frac{1}{\xi-x} - \frac{1}{\xi+x} \right] dx$$

$$Im \mathcal{H}_q = \pi e^2 q (H^q(\xi, \xi, t) - H^q(-\xi, \xi, t))$$



see H. Moutarde's talk

GPDs will enter in the observables through the Compton Form Factors and electromagnetic Form Factors:



$$\sigma = |BH|^2 + I(BH \cdot DVCS) + |DVCS|^2$$

### 1. Beam-Spin Asymmetry:

$$\Delta\sigma_{LU} \propto \sin\varphi \operatorname{Im}\{F_1 \mathcal{H} + \xi(F_1 + F_2) \tilde{\mathcal{H}} + kF_2 \mathcal{E}\} d\varphi$$

$$\begin{aligned} &\operatorname{Im}\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\} \\ &\operatorname{Im}\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\} \end{aligned}$$

### 2. Target-Spin Asymmetry:

$$\Delta\sigma_{UL} \propto \sin\varphi \operatorname{Im}\{F_1 \tilde{\mathcal{H}} + \xi(F_1 + F_2) \mathcal{H} + kF_2 \mathcal{E}\} d\varphi$$

$$\begin{aligned} &\operatorname{Im}\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\} \\ &\operatorname{Im}\{\mathcal{H}_n, \mathcal{E}_n, \tilde{\mathcal{E}}_n\} \end{aligned}$$

### 3. Double-Spin Asymmetry:

$$\Delta\sigma_{LL} \propto (A + B\cos\varphi) \operatorname{Re}\left\{F_1 \tilde{\mathcal{H}} + \xi(F_1 + F_2) \left(\mathcal{H} + \frac{x_B}{2} \mathcal{E}\right)\right\} d\varphi$$

$$\begin{aligned} &\operatorname{Re}\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\} \\ &\operatorname{Re}\{\mathcal{H}_n, \mathcal{E}_n, \tilde{\mathcal{E}}_n\} \end{aligned}$$

### 4. Transverse Target-Spin Asymmetry:

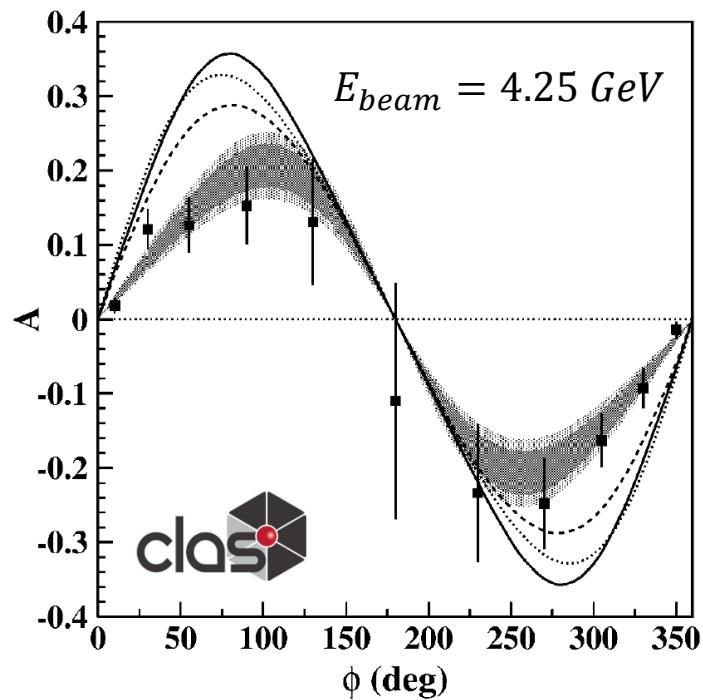
$$\Delta\sigma_{UT} \propto \sin\varphi \operatorname{Im}\{k(F_2 \mathcal{H} - F_1 \mathcal{E}) + \dots\} d\varphi$$

$$\begin{aligned} &\operatorname{Im}\{\mathcal{H}_p, \mathcal{E}_p\} \\ &\operatorname{Im}\{\mathcal{H}_n\} \end{aligned}$$

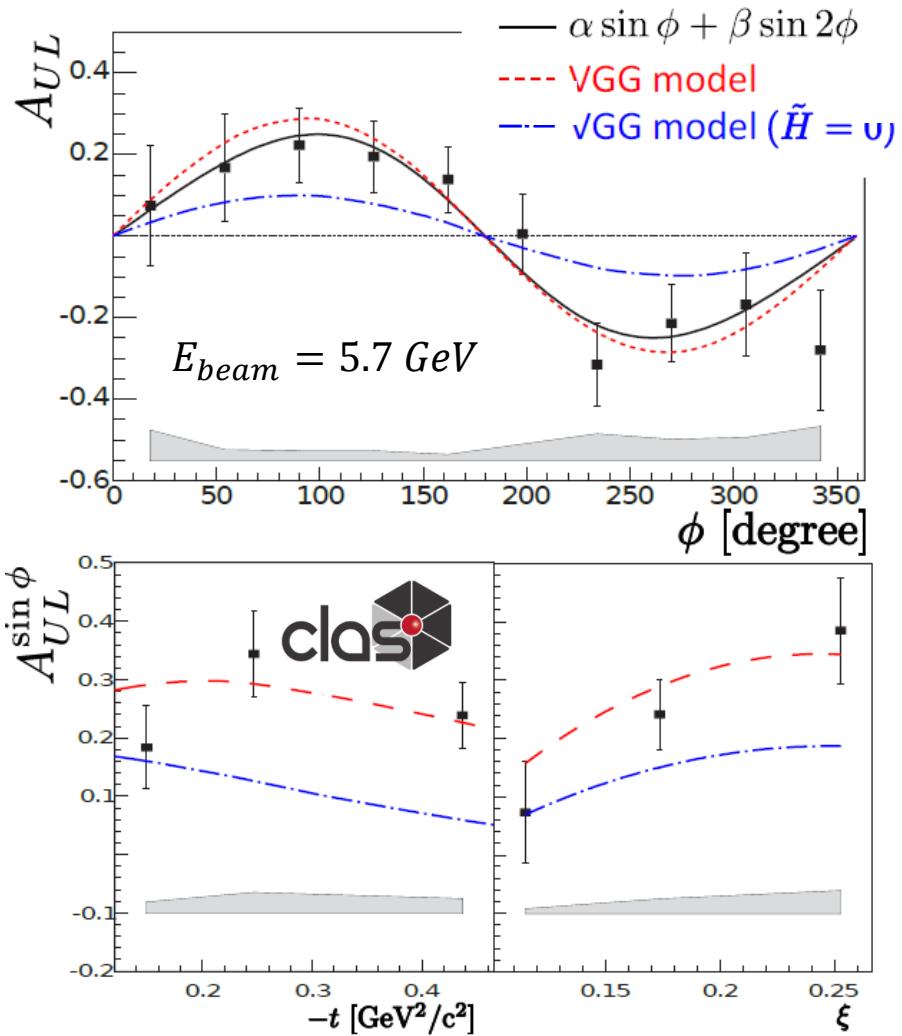
# Hall-B/CLAS: First observations of $A_{LU}$ & $A_{UL}$



→ signal of the Bethe-Heitler and DVCS interference observed already at CLAS6 kinematics.



S. Stepanyan et al., Phys. Rev. Lett. 87, 182002 (2001).

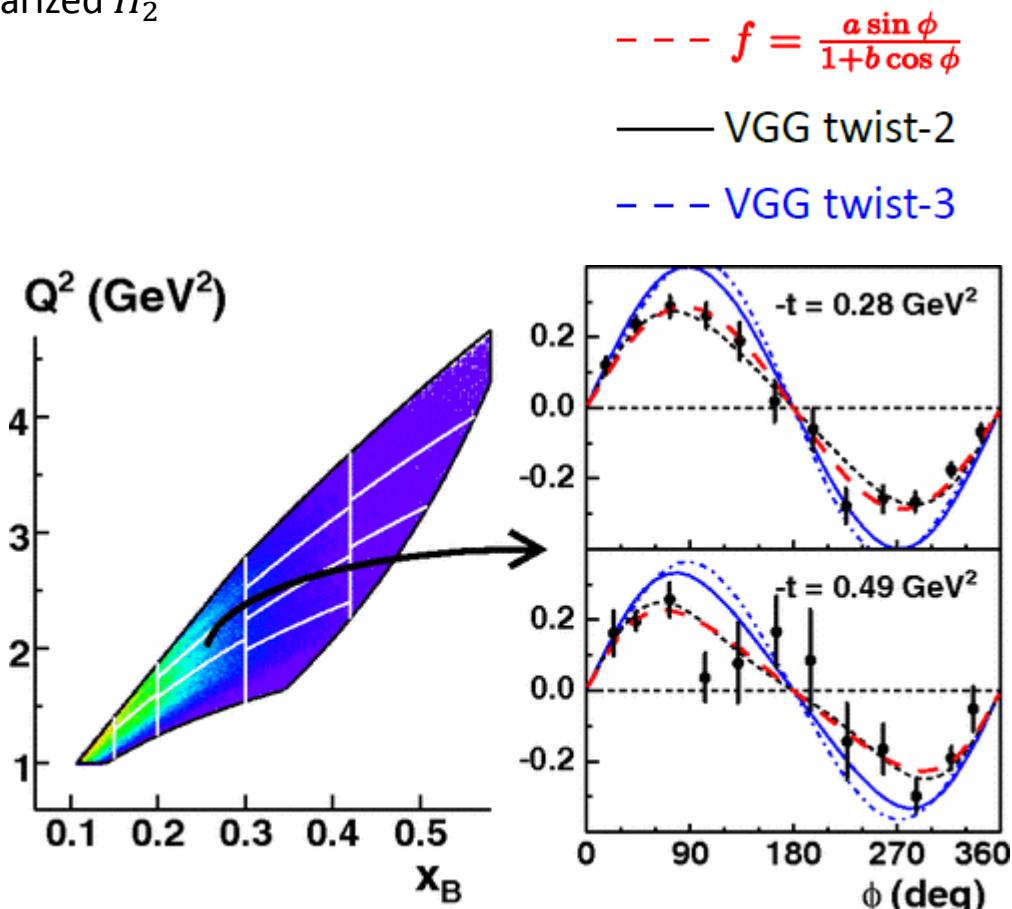
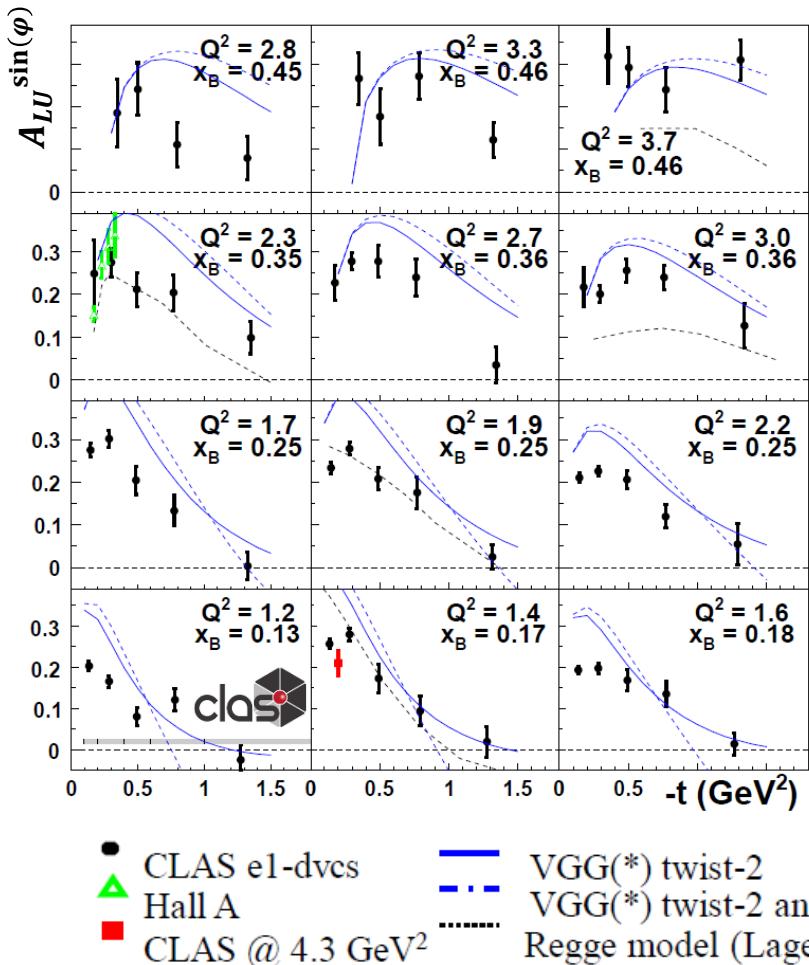


S. Chen et al., Phys. Rev. Lett. 97, 072002 (2006).

# Hall-B/CLAS: High-statistics $A_{LU}$ extraction on $H_2$ (E01-113)

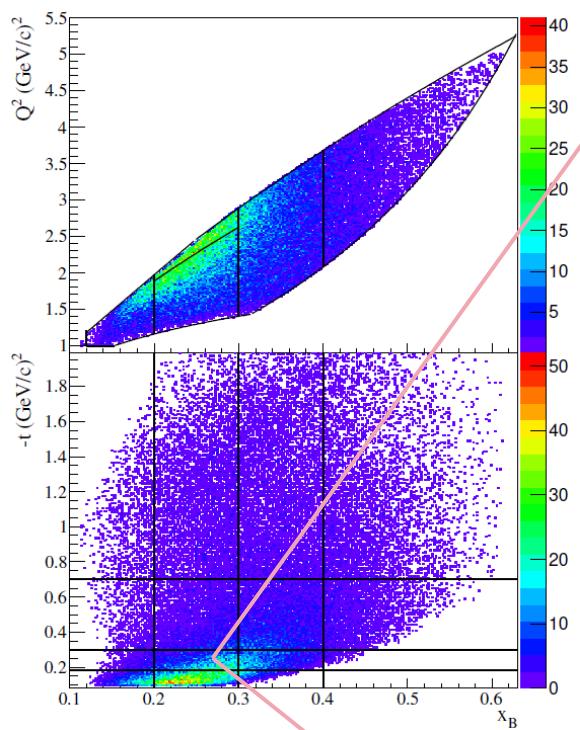


First CLAS DVCS devoted experiment on unpolarized  $H_2$



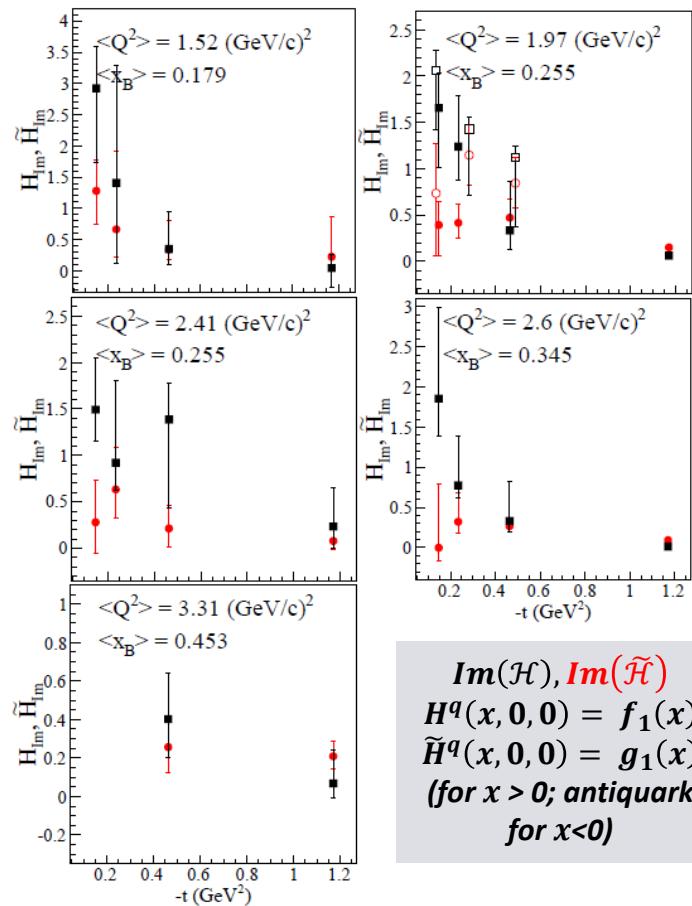
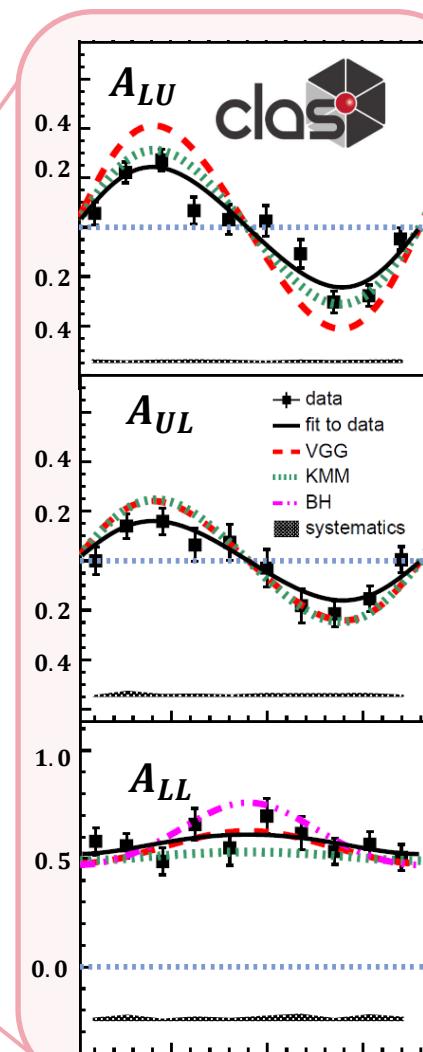
F. X. Girod et al., Phys. Rev. Lett. 100, 162002 (2008).

# Hall-B/CLAS: $A_{LU}$ , $A_{UL}$ , $A_{LL}$ extraction on $NH_3$ (E05-114)



High statistics extraction of Single and Double-Spin Asymmetries

→ simultaneous CFF extraction from three observables in a common kinematics



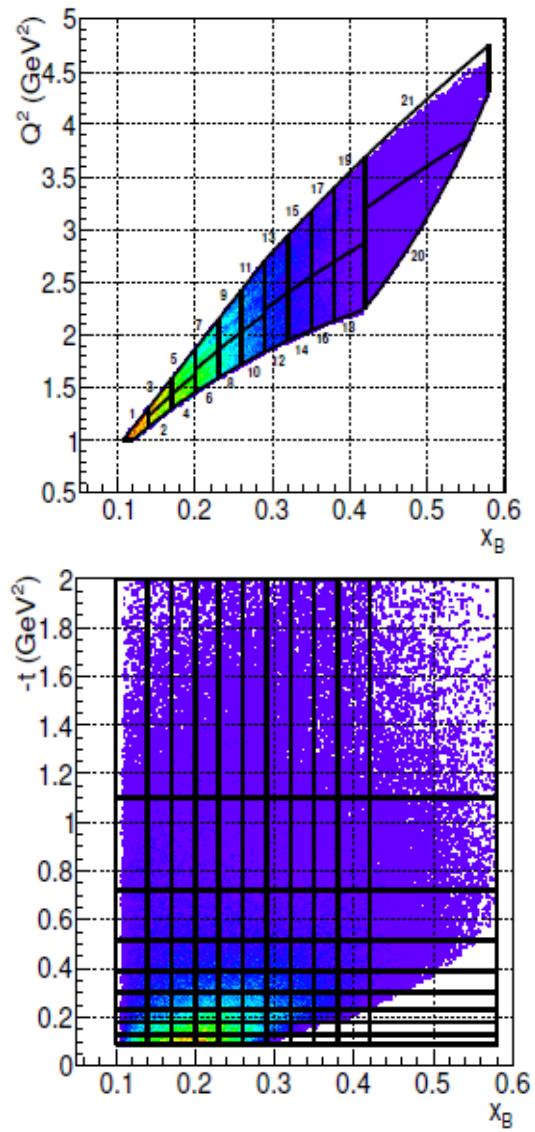
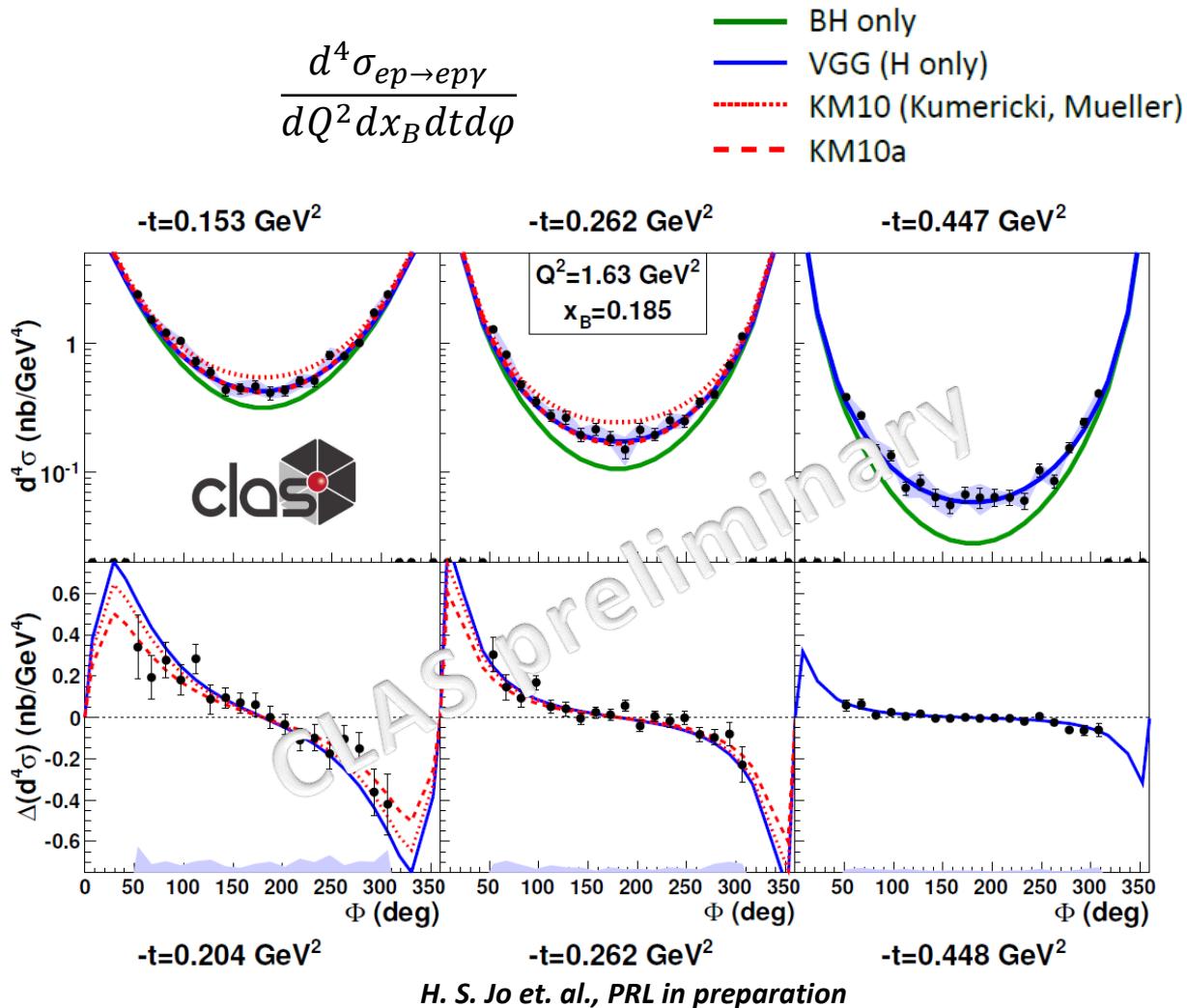
$Im(\mathcal{H}), Im(\tilde{\mathcal{H}})$   
 $H^q(x, 0, 0) = f_1(x)$   
 $\tilde{H}^q(x, 0, 0) = g_1(x)$   
 (for  $x > 0$ ; antiquark  
 for  $x < 0$ )

E. Seder et al, Phys. Rev. Lett. 114, 032001 (2015)  
 S.P. et al, arXiv:1501.07052 [hep-ex] – accepted by PRD

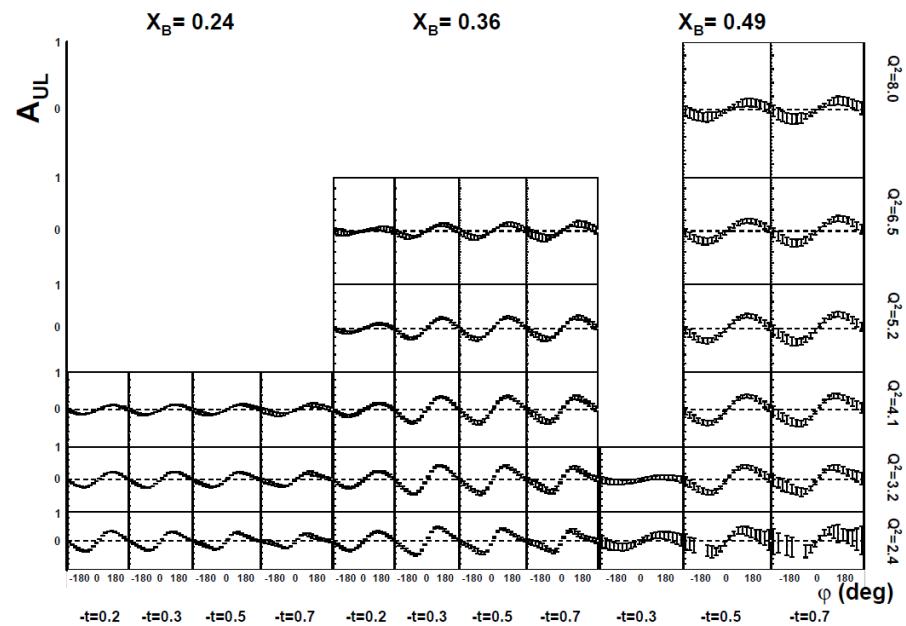
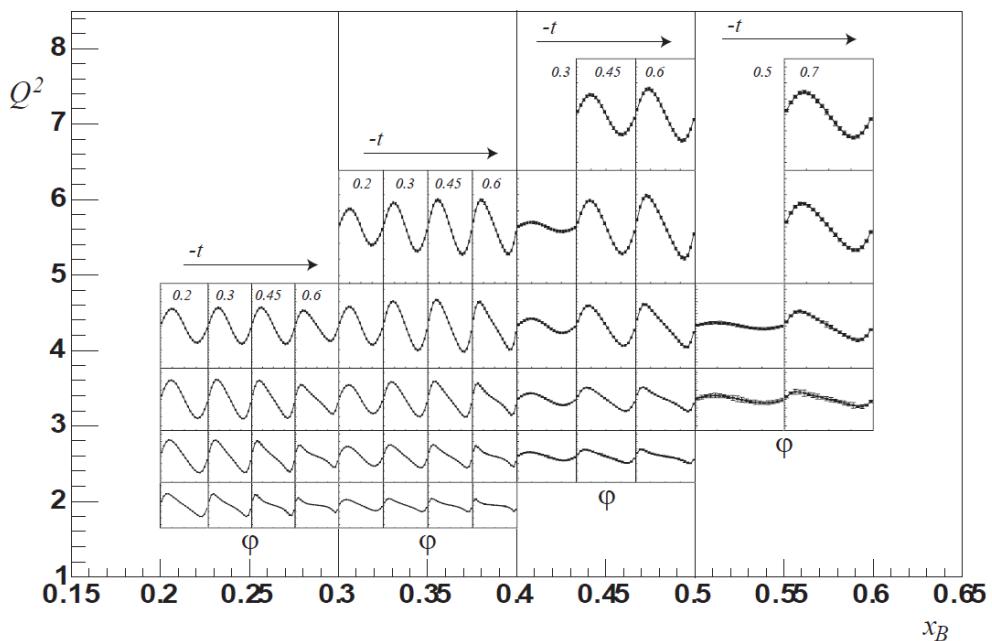
# Hall-B: DVCS cross-section on the proton in Hall-B (E01-113)



Extraction in a LARGE kinematic domain (110 bins)



$$\Delta\sigma_{LU} \propto \sin \varphi \operatorname{Im}\{F_1 \mathcal{H} + \xi(F_1 + F_2) \widetilde{\mathcal{H}} + kF_2 \mathcal{E}\} d\varphi \quad \Delta\sigma_{UL} \propto \sin \varphi \operatorname{Im}\{F_1 \widetilde{\mathcal{H}} + \xi(F_1 + F_2) \mathcal{H} + kF_2 \mathcal{E}\} d\varphi$$



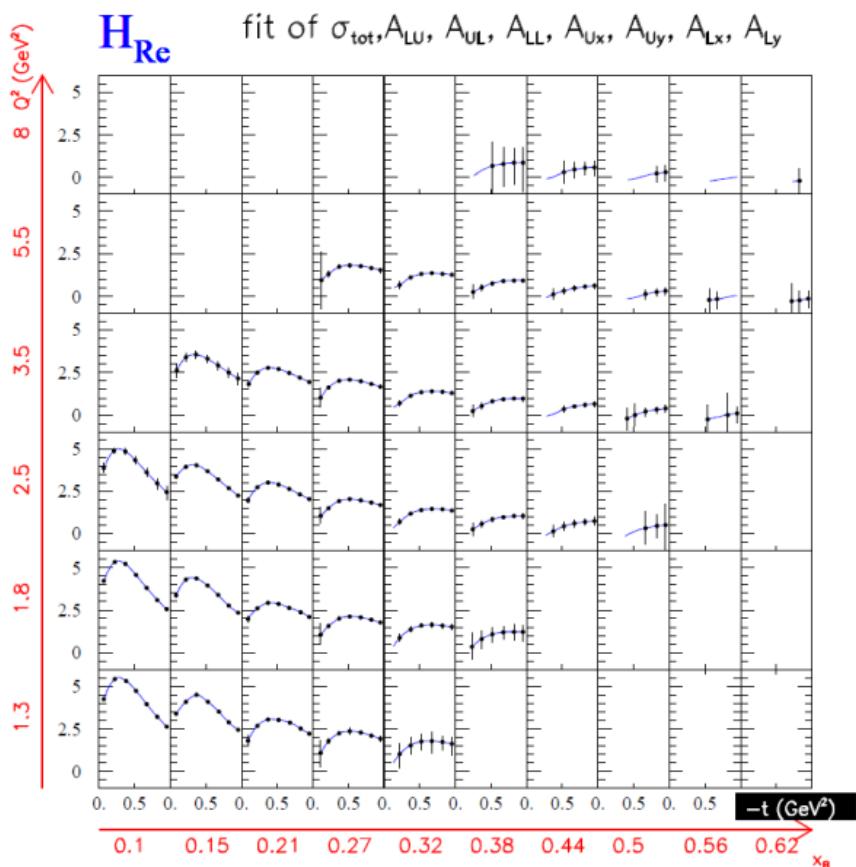
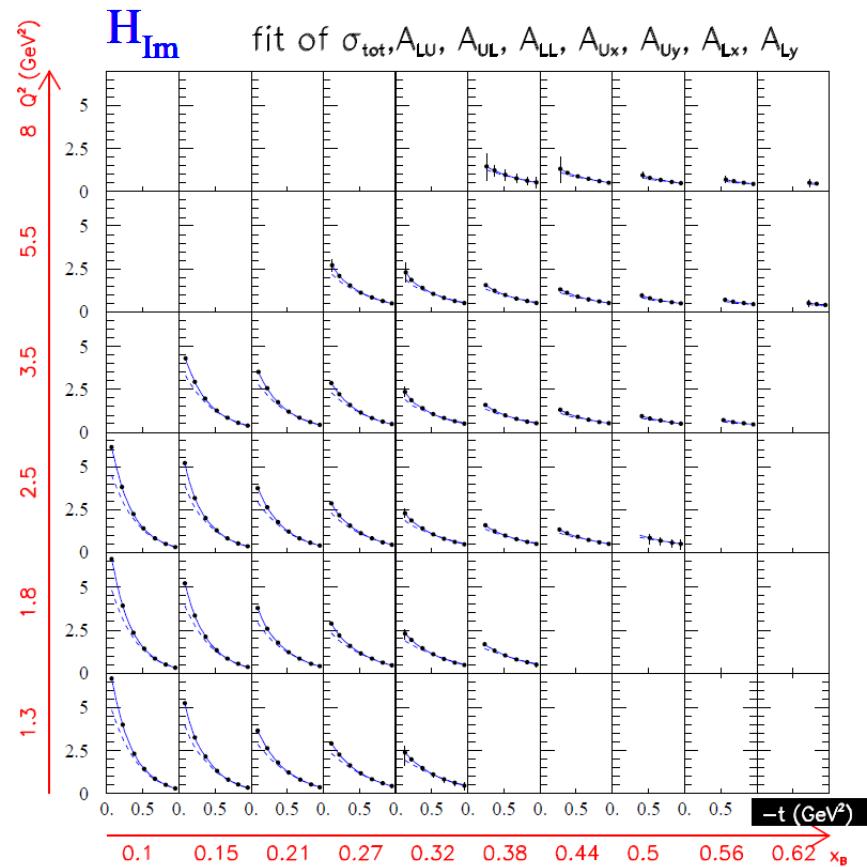
85 days on unpolarized  $H_2$  @  $10^{35} cm^{-2}s^{-1}$   
 120 days on longitudinally polarized  $NH_3$  @  $2 \times 10^{35} cm^{-2}s^{-1}$

# JLab 12 GeV data: impact on $\mathcal{H}$



- $\varphi$ -distributions in any  $(x_B, -t, Q^2)$  bin generated through VGG model
- CLAS acceptance & efficiencies included

see H. Moutarde's talk



M. Guidal, H. Moutarde, M. Vanderhaeghen: hep-ph > arXiv:1303.6600

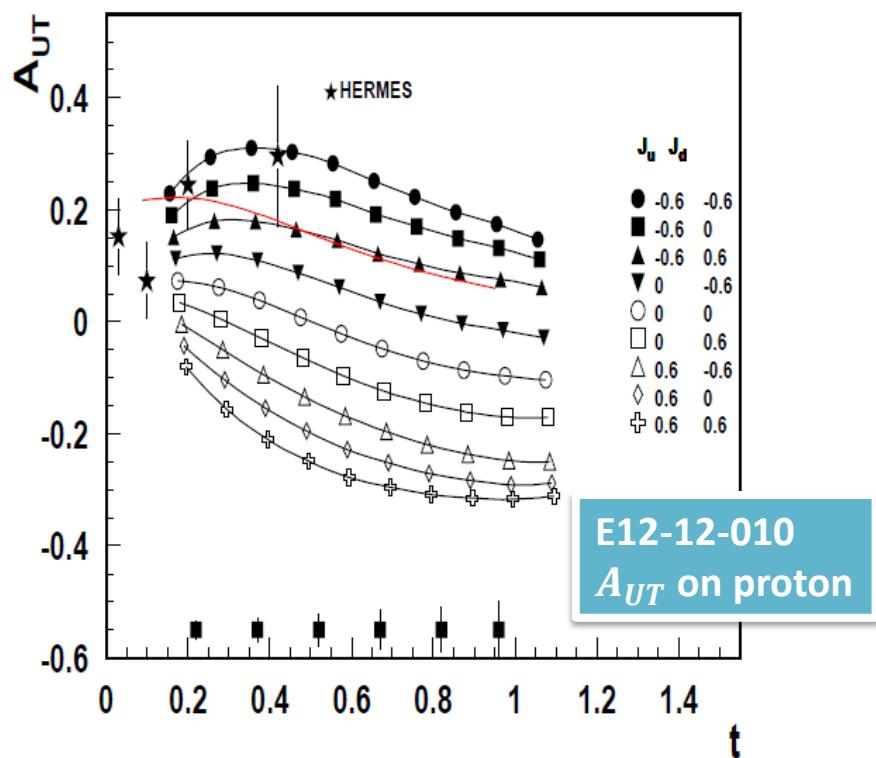
$$J_q = \frac{1}{2} \int_{-1}^{+1} dx x [H^q(x, \xi, t=0) + E^q(x, \xi, t=0)]$$

$$(H, E)_u(\xi, \xi, t) = \frac{9}{15} [4(H, E)_p(\xi, \xi, t) - (H, E)_n(\xi, \xi, t)]$$

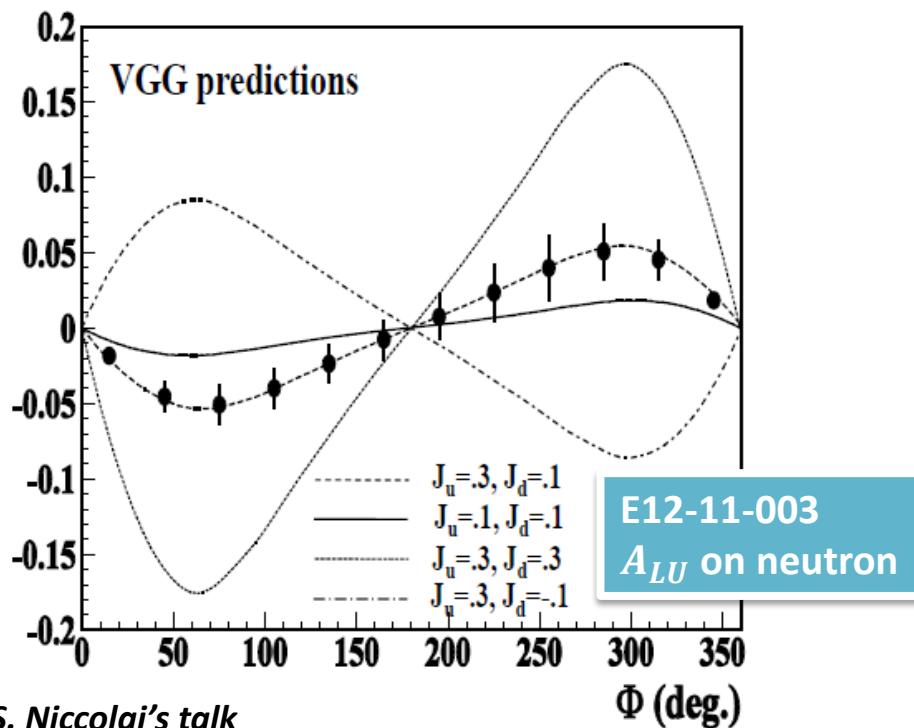
To access  $E_u$  &  $E_d$  both  $E_p$  &  $E_n$  are needed.

$$(H, E)_d(\xi, \xi, t) = \frac{9}{15} [4(H, E)_n(\xi, \xi, t) - (H, E)_p(\xi, \xi, t)]$$

**Proton GPD  $E_p$ :**  $\cos \varphi$  modulation in  $\sigma_{UT}$  on proton

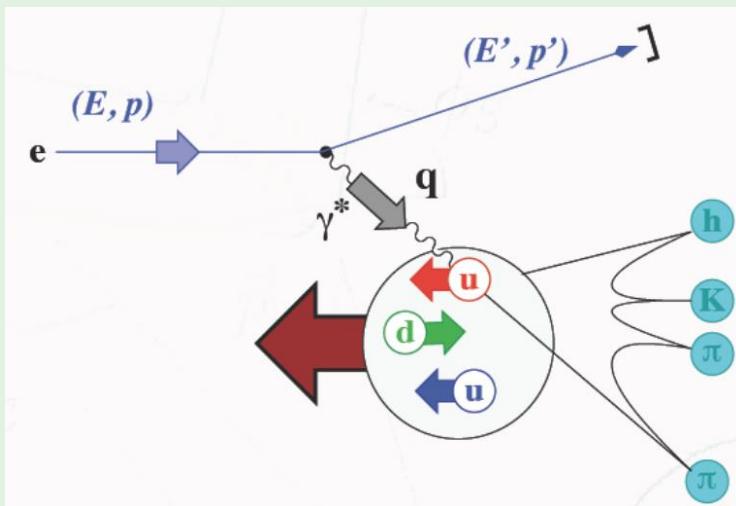


**Neutron GPD  $E_n$ :**  $A_{LU}$  on the neutron



See S. Niccolai's talk

# Transverse Momentum Distributions through Semi-Inclusive Deep-Inelastic Scattering



3D description of the nucleon structure in the momentum space → full 3D dynamics of the partons

Transition from hadronic to partonic degrees of freedom → Fragmentation Functions & Hadronization mechanisms

Hidden strangeness in the nucleon

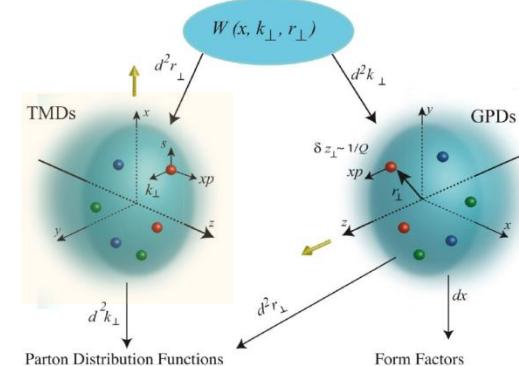
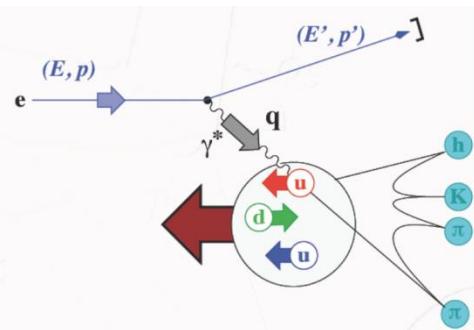
Access to quark-gluon-quark correlations through higher-twist observables

# Transverse Momentum Dependent PDFs&FFs

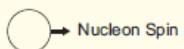


8 leading-twist TMDs

They depend on the parton longitudinal fraction  $x$  and on its transverse momentum  $k_T \rightarrow \text{full 3D dynamics}$



Leading Twist TMDs



		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \bullet$		$h_1^\perp = \bullet - \bullet$ Boer-Mulders
	L		$g_{1L} = \bullet \rightarrow - \bullet \rightarrow$ Helicity	$h_{1L}^\perp = \bullet \rightarrow - \bullet \rightarrow$
	T	$f_{1T}^\perp = \bullet \uparrow - \bullet \downarrow$ Sivers	$g_{1T}^\perp = \bullet \uparrow - \bullet \uparrow$	$h_{1T}^\perp = \bullet \uparrow - \bullet \uparrow$ Transversity

Fragmentation Functions  $\rightarrow$  transition from partonic to hadronic degrees of freedom

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

# Single-hadron SIDIS cross-section

Depending on the degrees of freedom active in the process, various TMDs&FFs can be accessed:

Unpolarized target  
Longitudinally pol. target  
Transversely pol. target

$$\frac{d\sigma^h}{dx dy d\phi_S dz d\phi d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\epsilon)} \left(1 + \frac{\gamma^2}{2x}\right)$$

$$\left\{ \begin{array}{l} \left[ F_{UU,T} + \epsilon F_{UU,L} \right. \\ \left. + \sqrt{2\epsilon(1+\epsilon)} \cos(\phi) F_{UU}^{\cos(\phi)} + \epsilon \cos(2\phi) F_{UU}^{\cos(2\phi)} \right] \\ + \lambda_l \left[ \sqrt{2\epsilon(1-\epsilon)} \sin(\phi) F_{LU}^{\sin(\phi)} \right] \\ + S_L \left[ \sqrt{2\epsilon(1+\epsilon)} \sin(\phi) F_{UL}^{\sin(\phi)} + \epsilon \sin(2\phi) F_{UL}^{\sin(2\phi)} \right] \\ + S_L \lambda_l \left[ \sqrt{1-\epsilon^2} F_{LL} + \sqrt{2\epsilon(1-\epsilon)} \cos(\phi) F_{LL}^{\cos(\phi)} \right] \\ + S_T \left[ \sin(\phi - \phi_S) \left( F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)} \right) \right. \\ \left. + \epsilon \sin(\phi + \phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \epsilon \sin(3\phi - \phi_S) F_{UT}^{\sin(3\phi-\phi_S)} \right. \\ \left. + \sqrt{2\epsilon(1+\epsilon)} \sin(\phi_S) F_{UT}^{\sin(\phi_S)} \right. \\ \left. + \sqrt{2\epsilon(1+\epsilon)} \sin(2\phi - \phi_S) F_{UT}^{\sin(2\phi-\phi_S)} \right] \\ + S_T \lambda_l \left[ \sqrt{1-\epsilon^2} \cos(\phi - \phi_S) F_{LT}^{\cos(\phi-\phi_S)} \right. \\ \left. + \sqrt{2\epsilon(1-\epsilon)} \cos(\phi_S) F_{LT}^{\cos(\phi_S)} \right. \\ \left. + \sqrt{2\epsilon(1-\epsilon)} \cos(2\phi - \phi_S) F_{LT}^{\cos(2\phi-\phi_S)} \right] \end{array} \right\}$$

18 structure functions appear in the cross-section

$$F_{ij,K} \propto DF \otimes FF$$

JLab TMD program explored the different terms:

1. Unpolarized contributions (Hall-B, Hall-C)
2. Longitudinally-polarized contributions (Hall-B)
3. Transversely-polarized contributions (Hall-A)

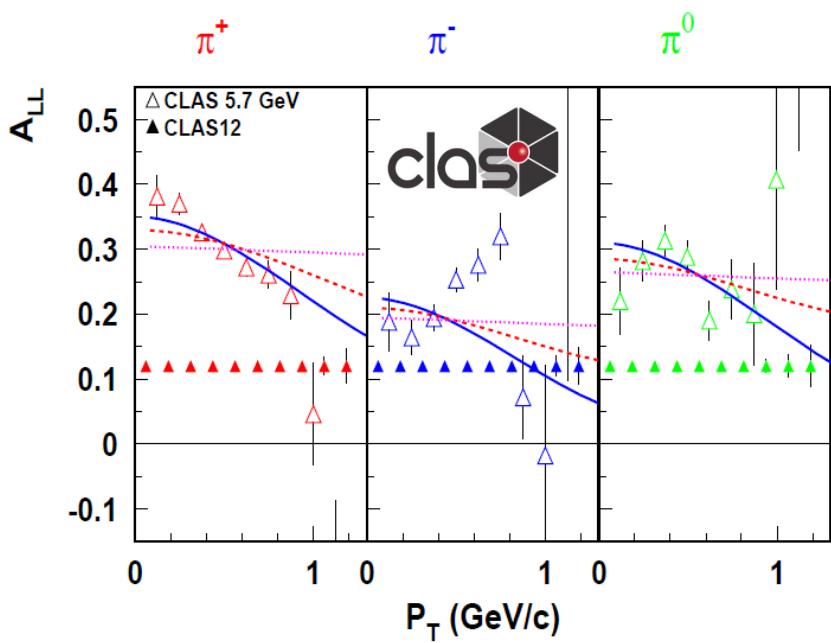
# Hall-B: diagonal TMDs $f_1, g_1$

$g_1, f_1$ :  $x$ -dependence extracted through Inclusive DIS

SIDIS needed to access  $p_T$  dependence

$$A_1 = A_{LL} \propto \frac{g_1 \otimes D_1}{f_1 \otimes D_1}$$

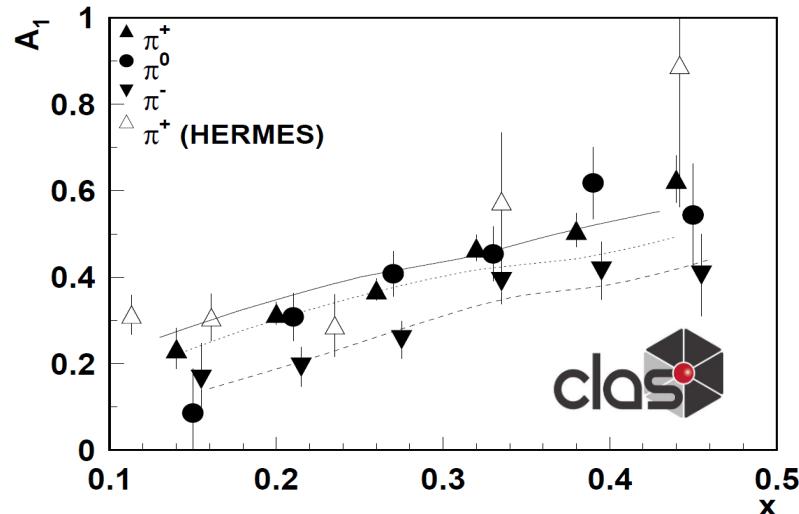
*H. Avakian et al., PRL105:  
262002 (2010)  
E12-07-107@12 GeV*



Curves: different  $R = \frac{k_\perp \text{ width of } g_1}{k_\perp \text{ width of } f_1}$

## Leading Twist TMDs

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \circlearrowleft$		$h_1^\perp = \begin{array}{c} \bullet \\ \circlearrowleft \end{array} - \begin{array}{c} \bullet \\ \circlearrowright \end{array}$ Boer-Mulders
	L		$g_{1L} = \begin{array}{c} \bullet \\ \circlearrowleft \end{array} \rightarrow \begin{array}{c} \bullet \\ \circlearrowright \end{array} \rightarrow$ Helicity	$h_{1L}^\perp = \begin{array}{c} \bullet \\ \circlearrowleft \end{array} \rightarrow \begin{array}{c} \bullet \\ \circlearrowright \end{array} \rightarrow$
	T	$f_{1T}^\perp = \begin{array}{c} \bullet \\ \circlearrowleft \end{array} - \begin{array}{c} \bullet \\ \circlearrowright \end{array}$ Sivers	$g_{1T}^\perp = \begin{array}{c} \bullet \\ \circlearrowleft \end{array} - \begin{array}{c} \bullet \\ \circlearrowright \end{array}$	$h_{1T}^\perp = \begin{array}{c} \bullet \\ \circlearrowleft \end{array} - \begin{array}{c} \bullet \\ \circlearrowright \end{array}$ Transversity $h_{1T}^\perp = \begin{array}{c} \bullet \\ \circlearrowleft \end{array} - \begin{array}{c} \bullet \\ \circlearrowright \end{array}$

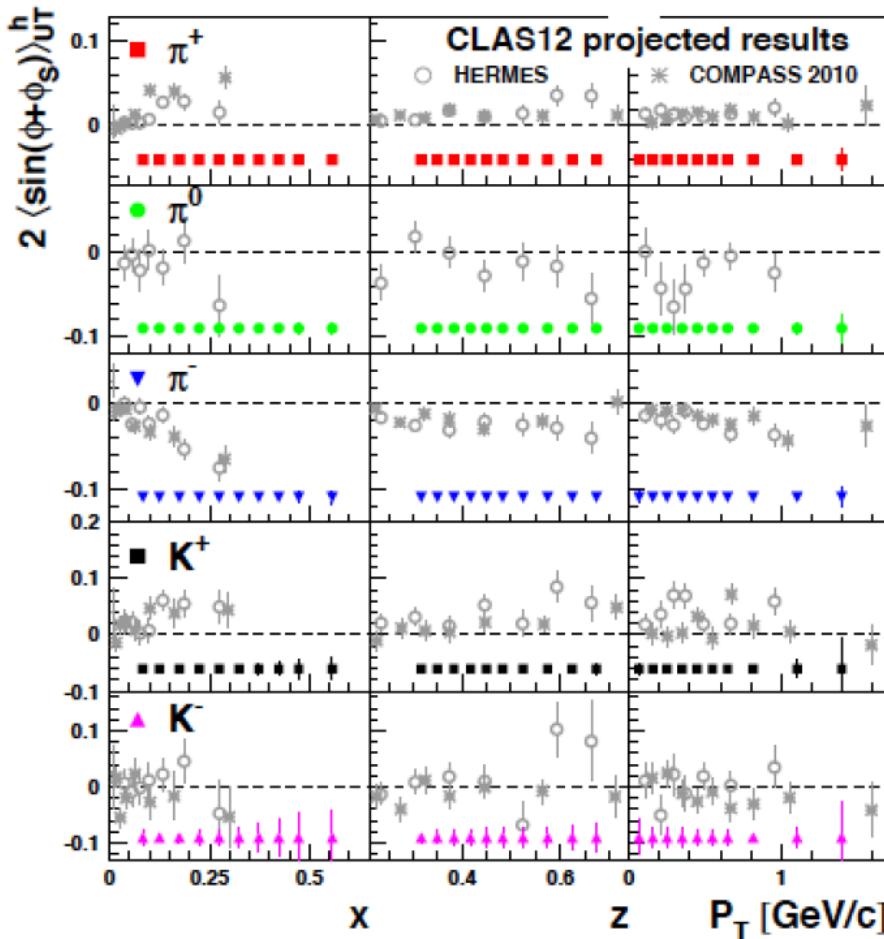


High-statistics (x10) extraction (S. Koirala, S. Jawalker Ph.D.) on 2009 data under analysis review.

# Diagonal TMDs: $h_1$ through 1h SIDIS (Collins effect)

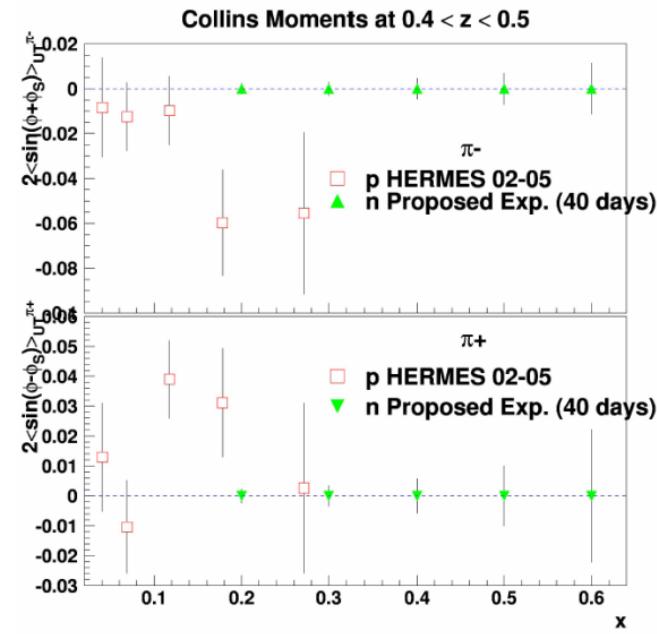


Hall-B@12 GeV: Collins effect on proton



- valence region almost unexplored
- discrepancy among  $\pi^+$  and  $k^+$  data (in the  $u$ -quark dominance picture)

Hall-A@12 GeV: Collins effect on neutron

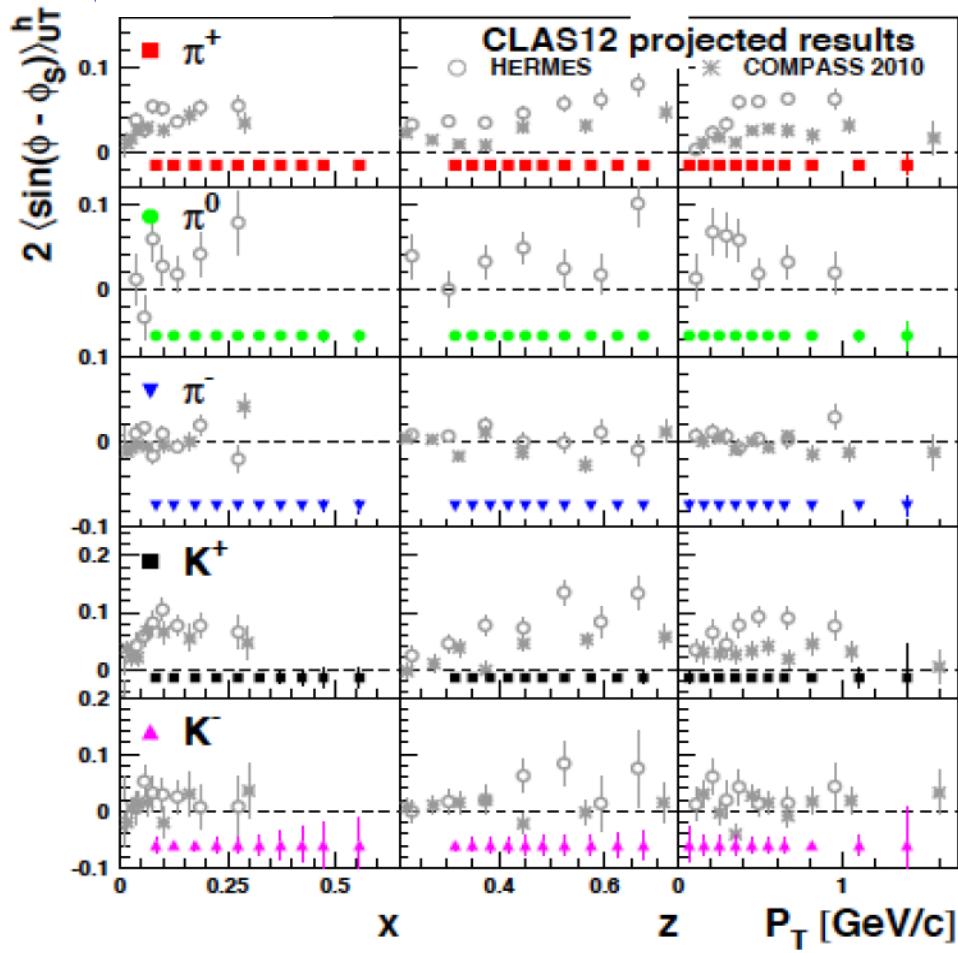


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# Sivers effect at 12 GeV

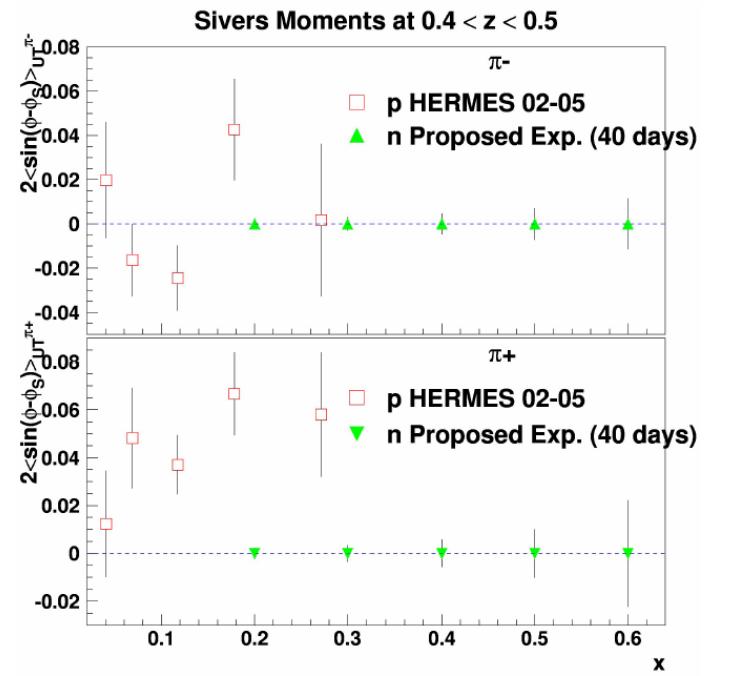


Hall-B@12 GeV: Sivers effect on proton



- valence region almost unexplored
- discrepancy in the  $z, p_T$ -distributions  
→ stronger evolution in the FF?

Hall-A@12 GeV: Sivers effect on neutron



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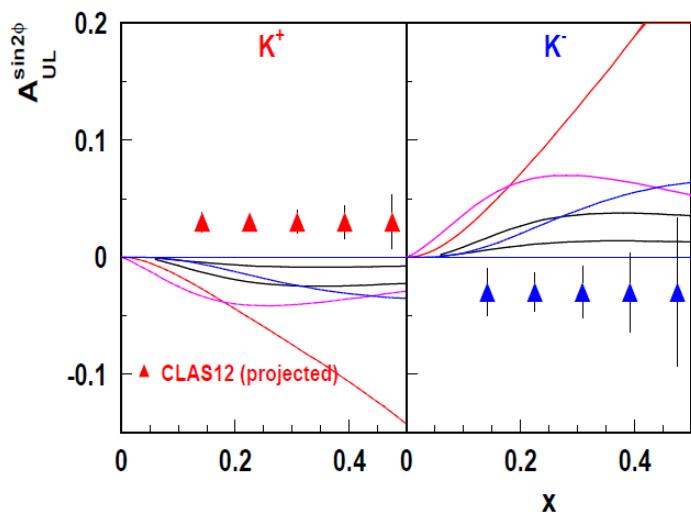
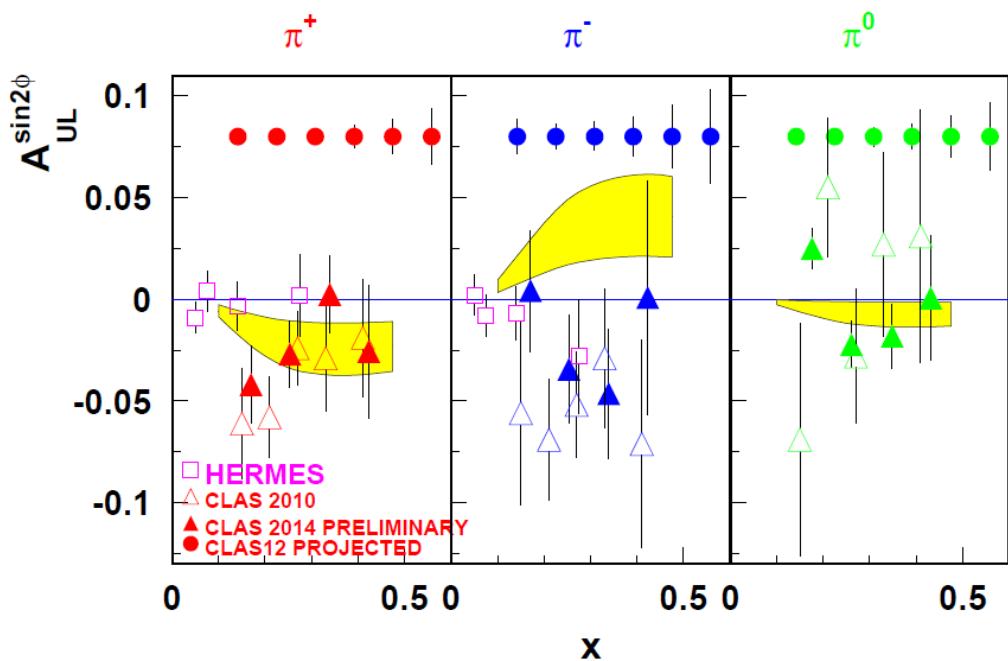
# Off-diagonal TMDs: Kotzinian-Mulder

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

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

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

		Leading Twist TMDs			
		Quark Polarization			
Nucleon Polarization	U	$f_1 = \bullet$	Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
	L			$g_{1L} = \bullet \rightarrow - \bullet$ Helicity	$h_{1L}^\perp = \bullet \rightarrow - \bullet$
	T	$f_{1T}^\perp = \bullet - \bullet$ Sivers	$g_{1T}^\perp = \bullet - \bullet$	$h_1^\perp = \bullet - \bullet$ Transversity	$h_{1T}^\perp = \bullet - \bullet$



H. Avakian et al., PRL105: 262002 (2010)  
E12-07-107 (pions), E12-009-009 (kaons) @12 GeV

# Higher-twist@Hall-B: $A_{LU}$ on unpolarized $H_2$

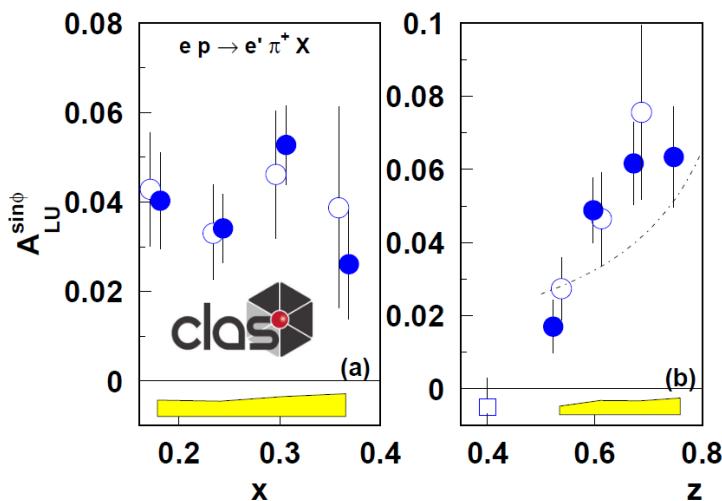


$A_{LU}$  is proportional to the structure function

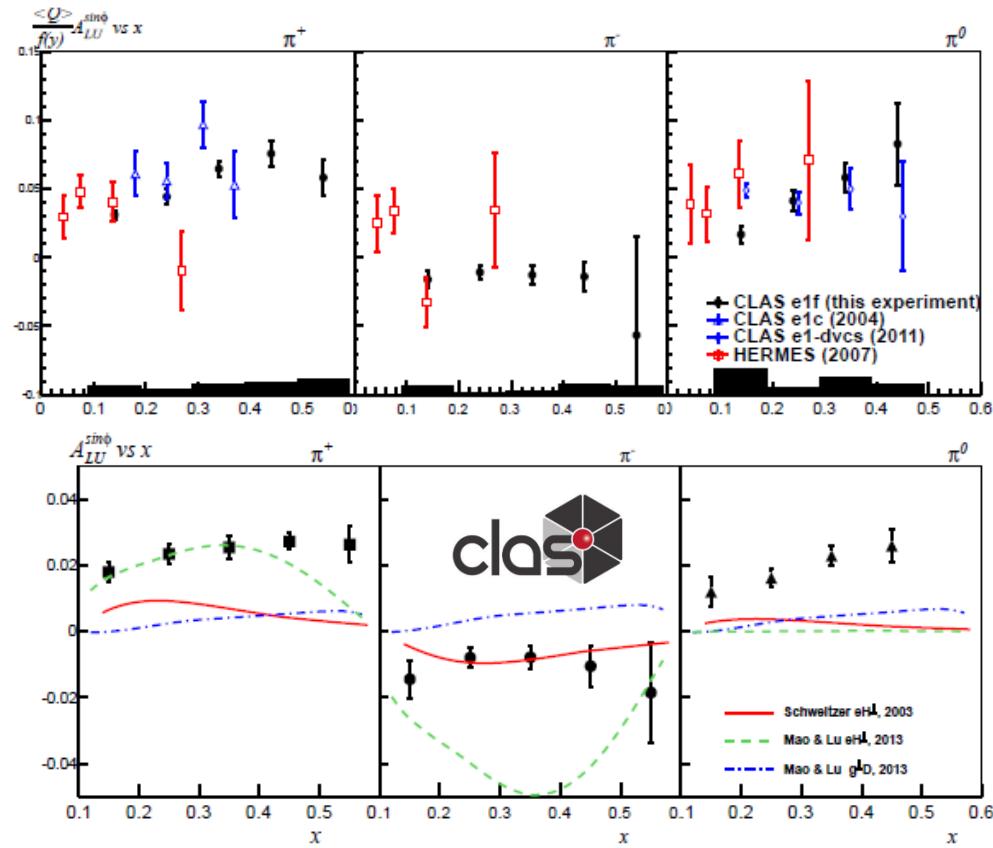
$$F_{LU}^{\sin \phi_h} = \frac{2M}{Q} \mathcal{C} \left[ -\frac{\hat{h} \cdot k_T}{M_h} \left( xe H_1^\perp + \frac{M_h}{M} f_1 \frac{\tilde{G}^\perp}{z} \right) + \frac{\hat{h} \cdot p_T}{M} \left( xg^\perp D_1 + \frac{M_h}{M} h_1^\perp \frac{\tilde{E}}{z} \right) \right]$$

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

H. Avakian *et al.*, PRD69, 112004 (2004)@4.3 GeV



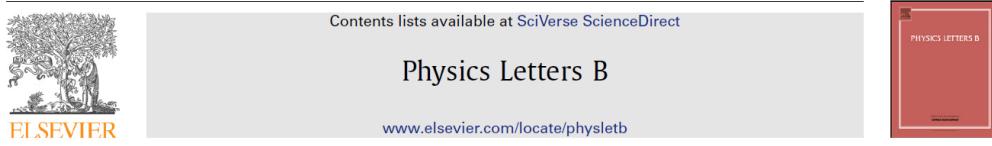
→ Entire structure function is twist-3, so in commonly used Wandzura-Wilczek approximation entire asymmetry = 0



# Back-to-back Semi-Inclusive DIS



- study correlations in target vs current
- control the flavor content of the final state hadron in current fragmentation (detecting the target hadron)
- access quark short-range correlations and  $\chi_{SB}$  (*Schweitzer et al*)



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

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<sup>b</sup> Di.S.T.A., Università del Piemonte Orientale "A. Avogadro", INFN, Gruppo Collegato di Alessandria, 15121 Alessandria, Italy  
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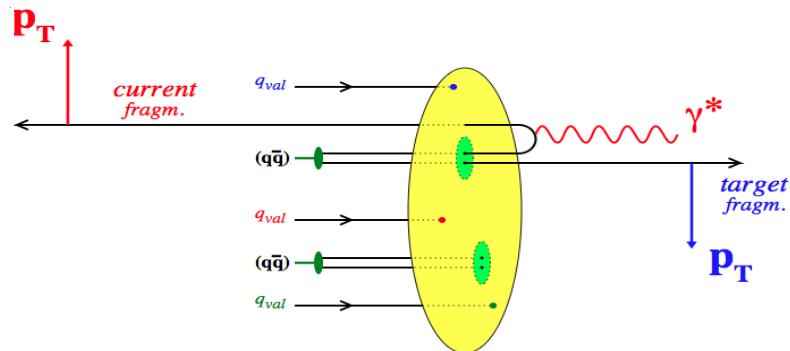
Keywords:  
Semi-inclusive DIS  
Target fragmentation  
Fracture functions  
Polarization  
Transverse momentum

## 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.

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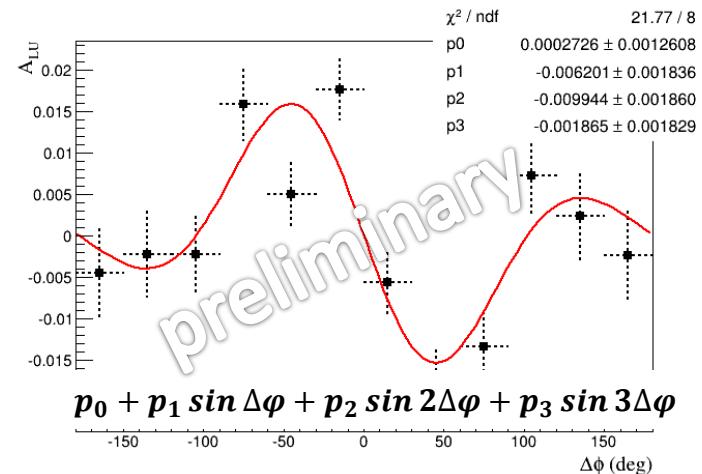
**Phys. Lett. B 713 (2012) 317**



Experimental signature of such a correlation:

$$\mathcal{F}_{LU}, \mathcal{F}_{UU} \propto P_{\perp 1} \cdot P_{\perp 2} = |P_1||P_2| \cos \Delta\phi$$

$\rightarrow \sin \Delta\phi \cos \Delta\phi \Rightarrow \text{series of } \sin n\Delta\phi \text{ terms}$



# Conclusions



CLAS, and in general Jefferson Lab experiments, had a high impact on the knowledge of the nucleon structure.

The 6-GeV era provided:

1. applicability of the partonic interpretation of the involved processes (DIS, DVCS & SIDIS)
2. constraints of the CFF  $\mathcal{H}, \tilde{\mathcal{H}}$  through DVCS  $A_{LU}, A_{UL}, A_{LL}$  and cross-sections & on SIDIS observables
3. Observation of higher-twist effect (SIDIS  $A_{LU}$ ) → quark-gluon correlations

12-GeV era will bring:

1. insights into the transverse degrees of freedom, both for DVCS and SIDIS, for proton and neutron → flavor separation
2. extraction of DVCS&SIDIS observable in a wider kinematics with the highest precision
3. information on the  $s$ -quark role inside the nucleon through kaon measurements

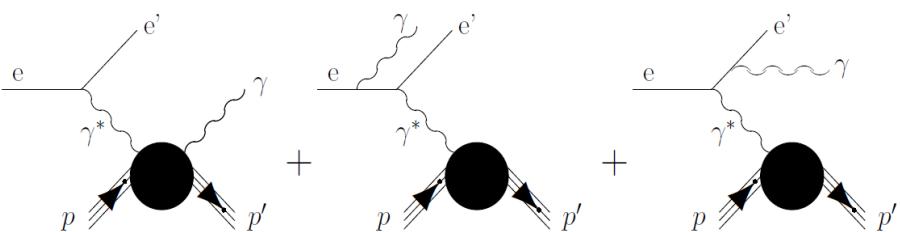
→ ***final goal: wide-coverage, high-statistics mapping of the 5D valence nucleon structure***

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# backup

# Experimental access to GPDs

Two processes contribute to the same  $(e, p, \gamma)$  final state: Bethe-Heitler and Deeply-Virtual Compton Scattering.

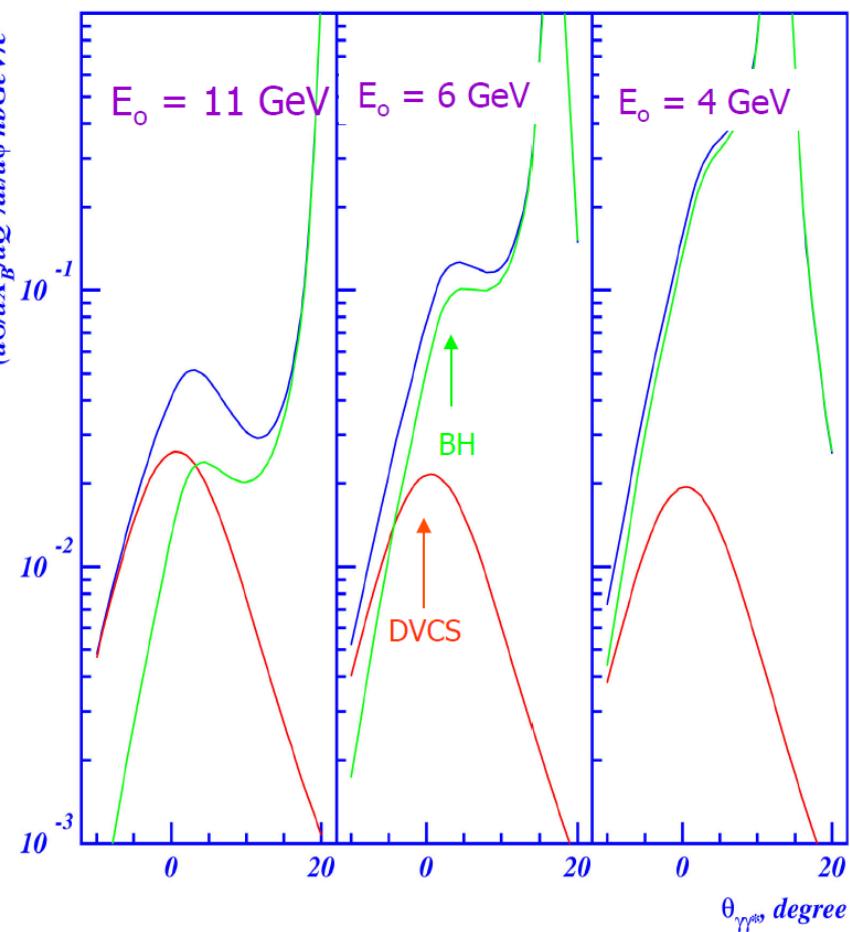


$$\sigma = |BH|^2 + I(BH \cdot DVCS) + |DVCS|^2$$

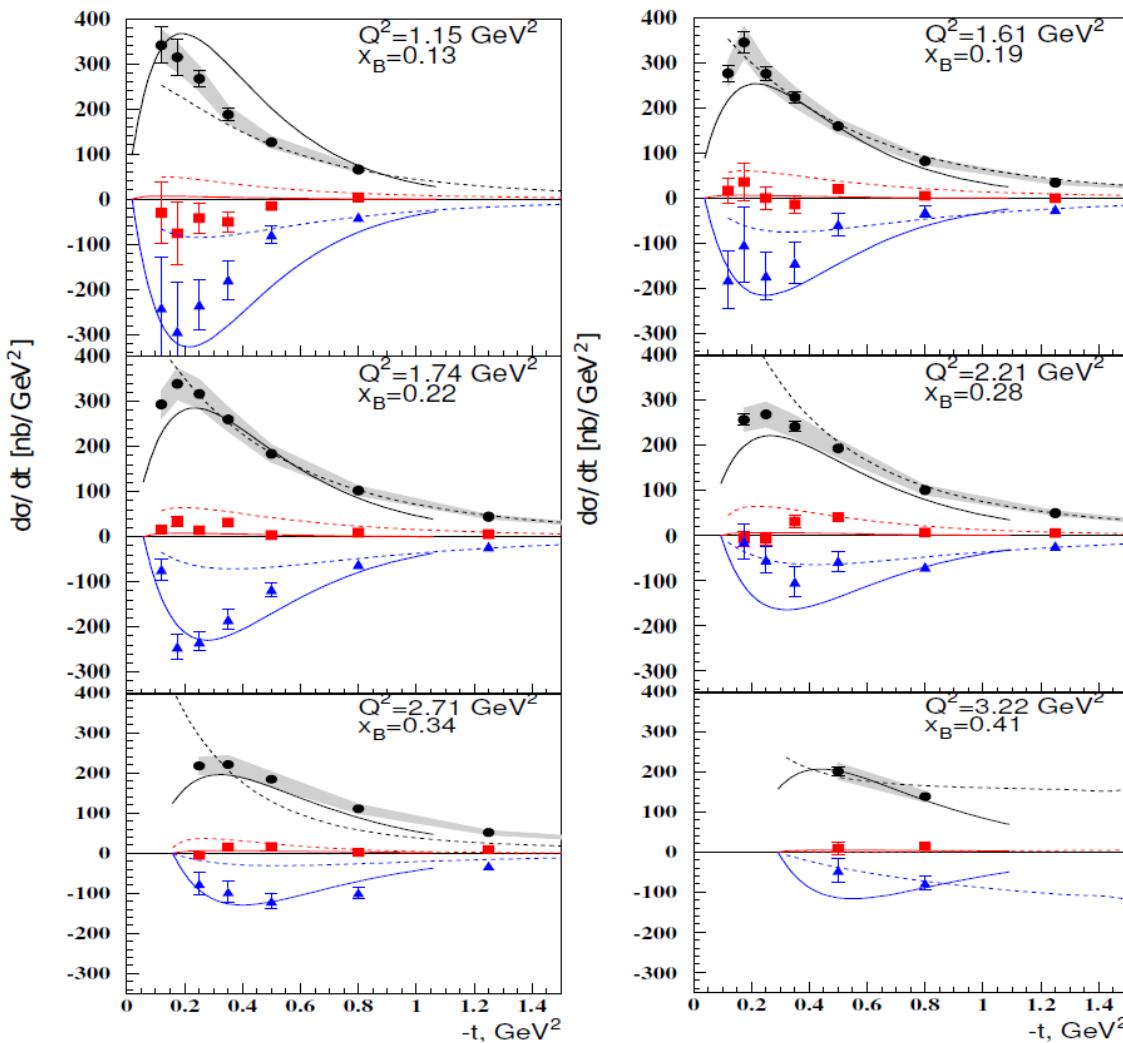


**$I(BH \cdot DVCS)$  gives rise to spin asymmetries, which can be connected to combinations of GPDs**

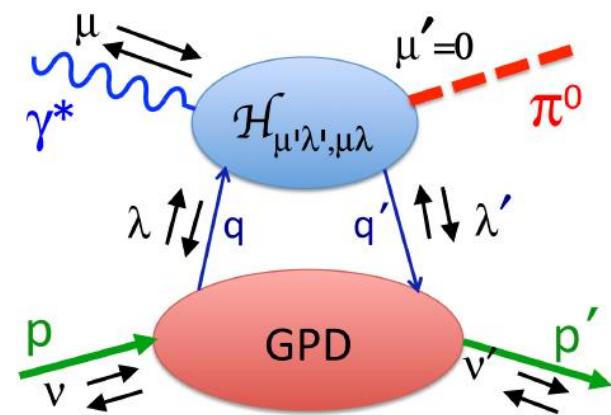
Cross section of  $ep \rightarrow ep\gamma$  at  $Q^2=2 \text{ GeV}/c^2$  and  $X_B=0.35$



# DV $\pi^0$ S cross-section on the proton in Hall-B (E01-113)



$\pi^0$  electroproduction → sensitivity to transversity GPDs



$$\sigma_T \sim (1 - \xi^2) |H_T|^2 - \frac{t'}{8m^2} |\bar{E}_T|^2$$

$$\begin{aligned} \text{--- } \sigma_0 &= \sigma_T + \epsilon \sigma_L \\ \text{--- } \sigma_{TT} &\\ \text{--- } \sigma_{LT} & \end{aligned}$$

$$\sigma_{TT} \sim \frac{t'}{8m^2} |\bar{E}_T|^2$$

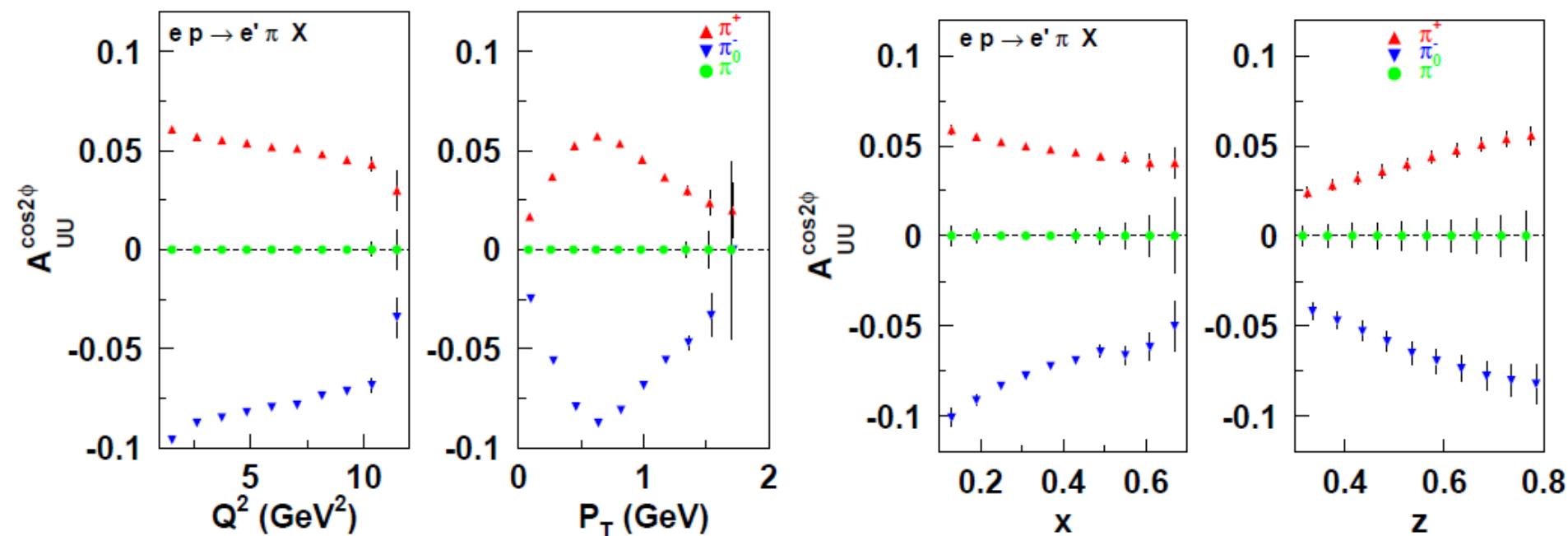
I. Bedlinskiy et al., PRL109:112001 (2012)

Transversely-polarized quark in an unpolarized proton

$\rightarrow \cos 2\phi_h$  modulation

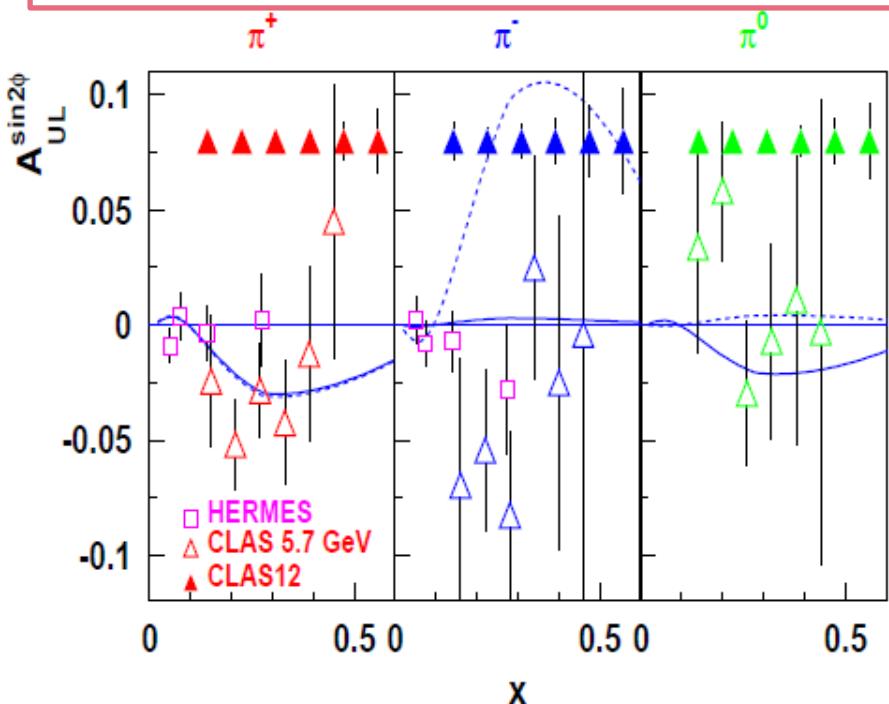
Wide  $x$ & $p_T$  range to map quark 3D momentum phase space

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

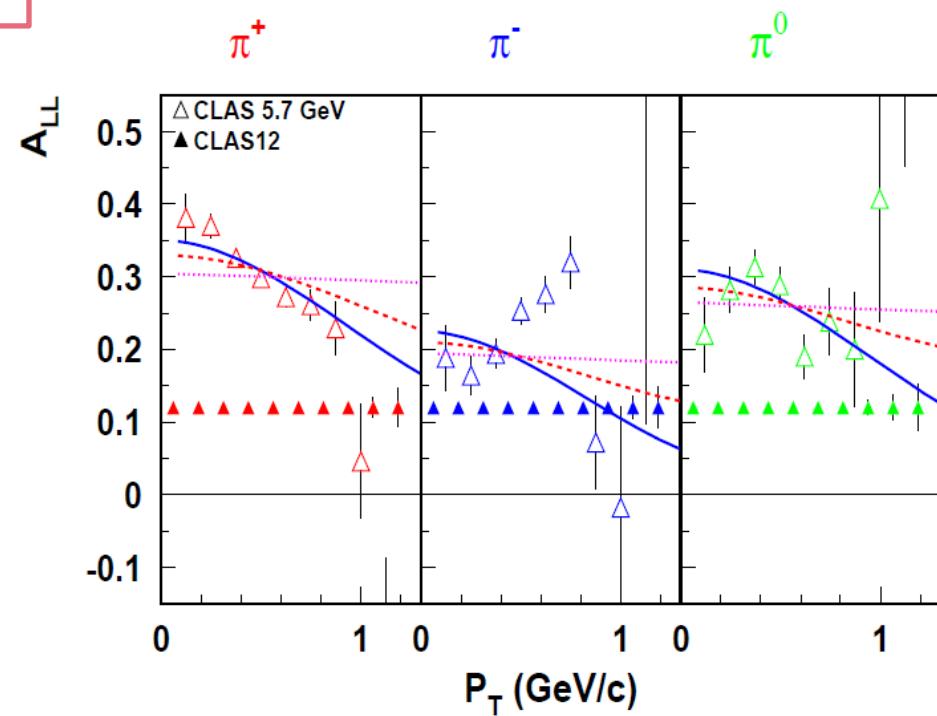


Longitudinal Target-Spin Asymmetry: Kotzinian-Mulder function → transversely-polarized quark in a longitudinally-polarized proton

Longitudinal Double-Spin Asymmetry:  
difference in the  $k_T$  distribution of quark with  
spin || or anti-|| to the proton spin



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



N/q	U	L	T
U	$f_1$		$h_1^\perp$
L		$\mathbf{g}_1$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}$	$\mathbf{h}_1, h_{1T}^\perp$

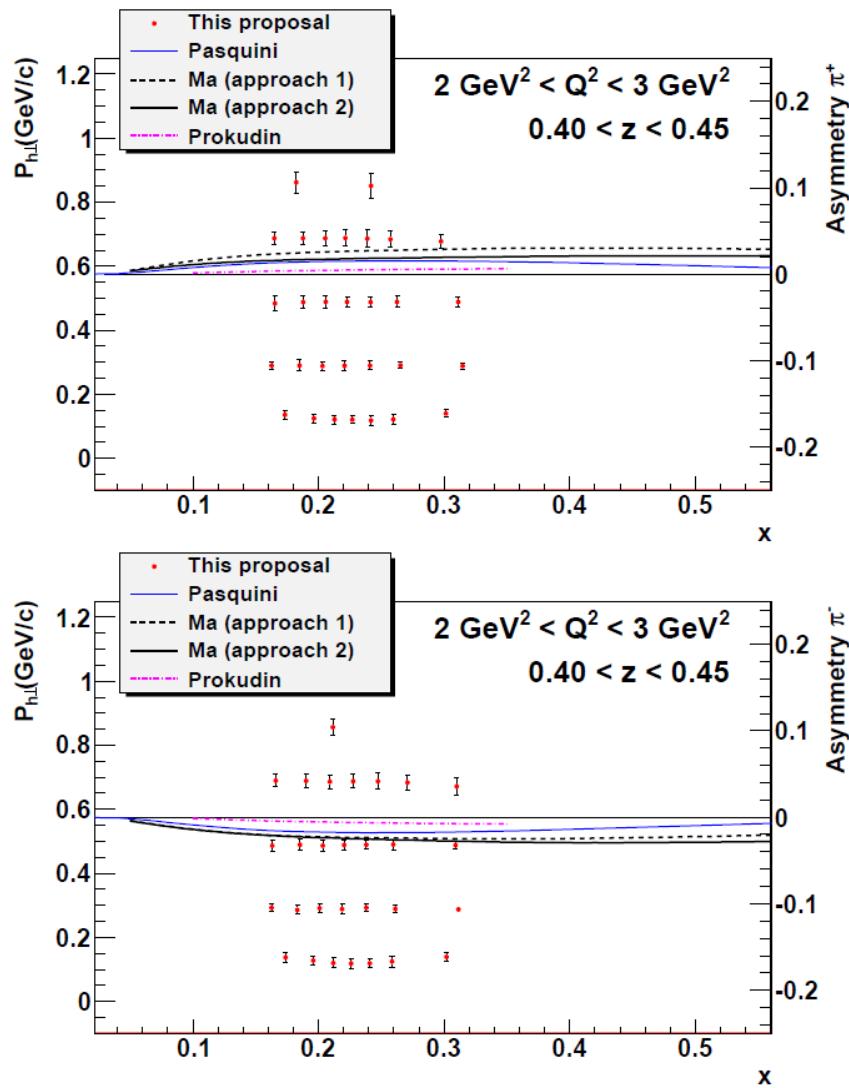
Measurement on NEUTRON

→ Can be combined with the Hall-B measurement on proton

Measurement on longitudinally and transversely polarized  ${}^3He$  target.

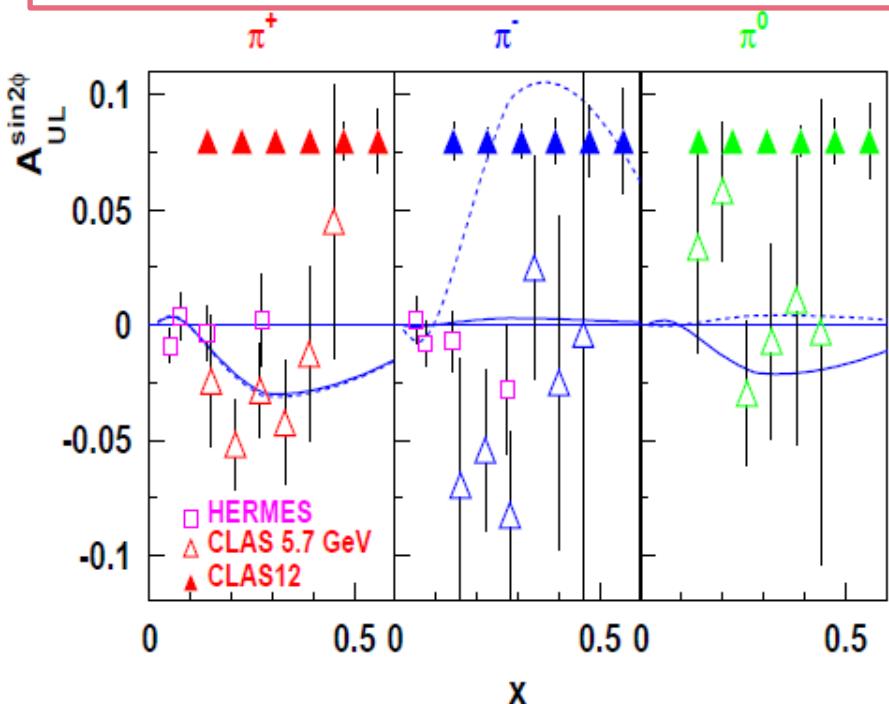
Combining the  $A_{LL}$  on neutron → constrain the flavour decomposition of the quark helicity distribution

4D binning in  $(x, z, p_\perp, Q^2)$

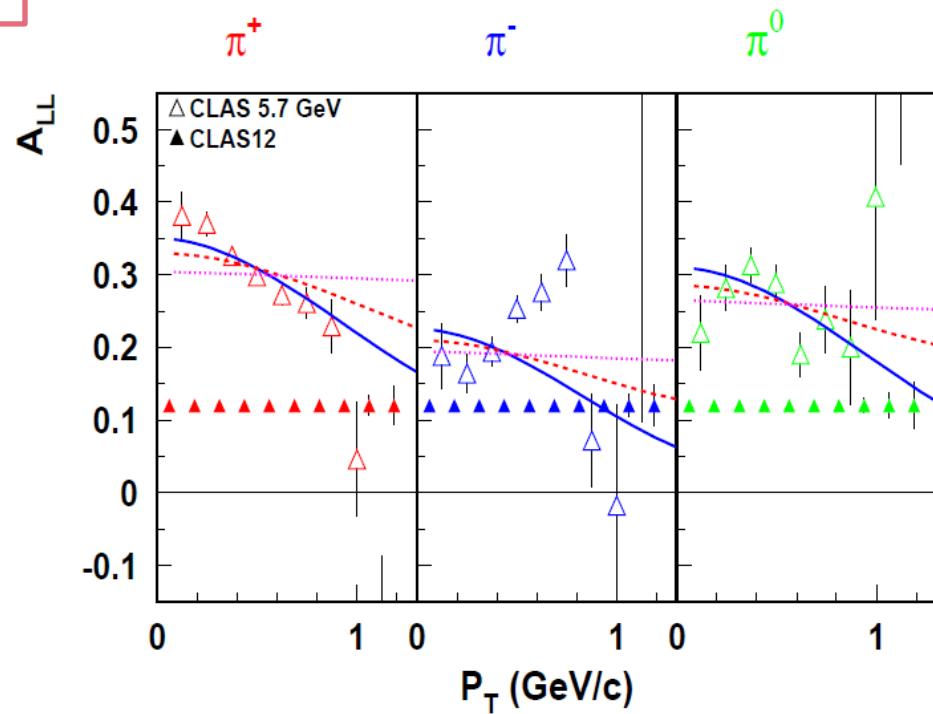


Longitudinal Target-Spin Asymmetry: Kotzinian-Mulder function → transversely-polarized quark in a longitudinally-polarized proton

Longitudinal Double-Spin Asymmetry:  
difference in the  $k_T$  distribution of quark with  
spin || or anti-|| to the proton spin



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



# $A_{UL}$ for kaons@Hall-B - E12-09-009



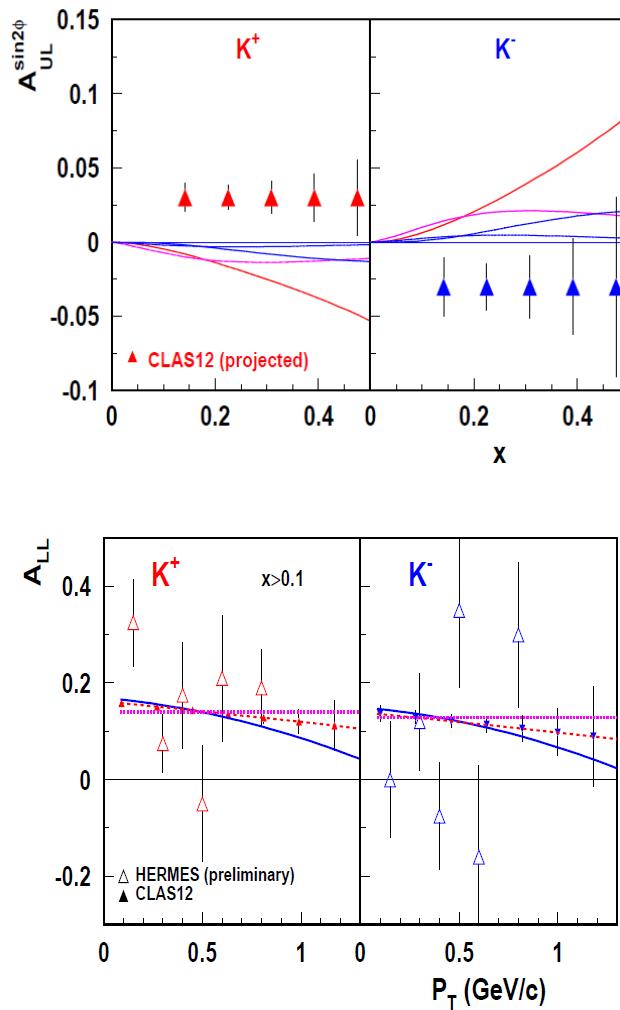
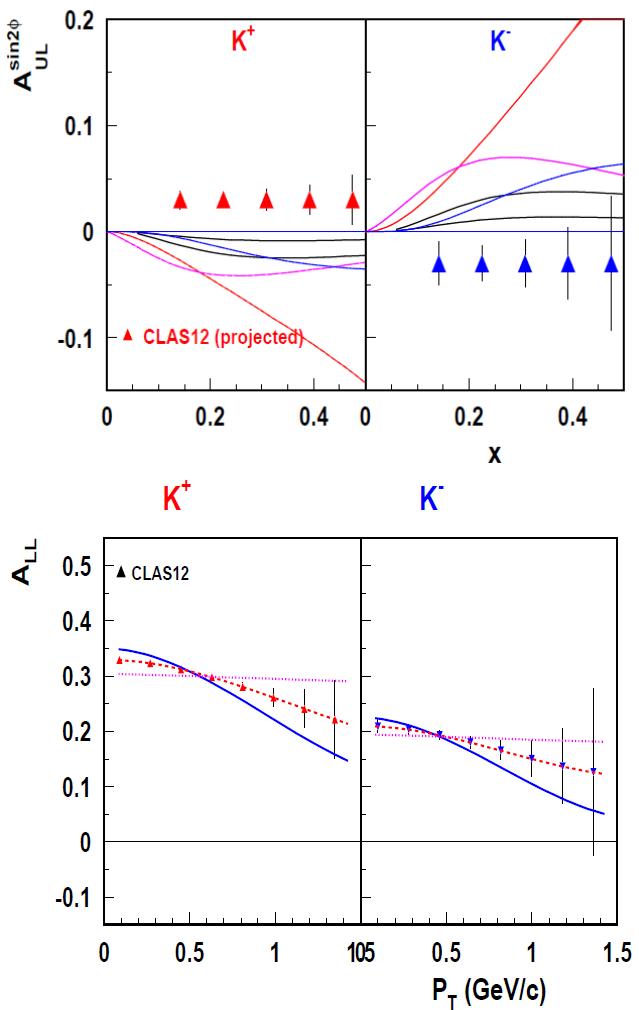
## Collins fragmentations of kaons

- test of the fragmentation mechanism in the presence of a  $s$ -quark
- distribution of the sea quarks on the nucleon

85 days of beam time

$P_{target} = 85\% (NH_3), 40\% (ND_3)$

$\mathcal{L} = 10^{35} cm^{-2}s^{-1}$

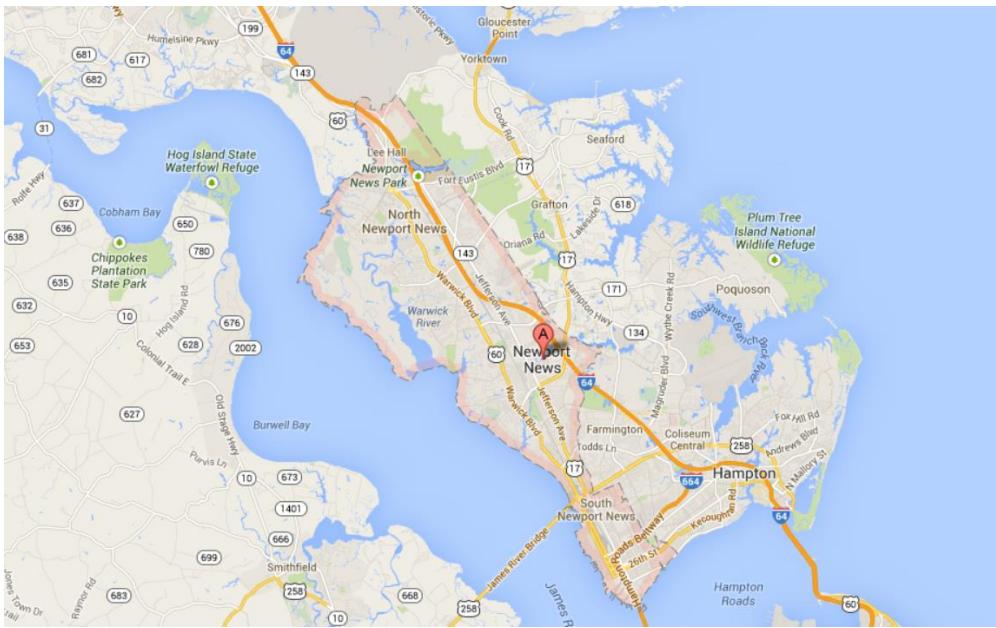


# Thomas Jefferson National Accelerator Facility



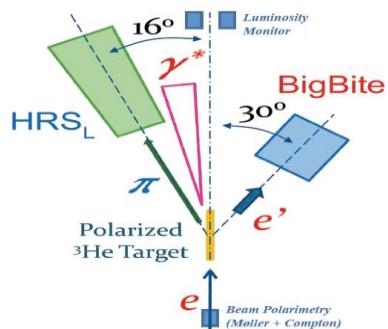
The **CEBAF (Continuous Electron Beams Accelerator Facility)** operates in the Thomas Jefferson National Accelerator Facility (Newport News, VA, USA). The Cebaf:

- provides a continuous electron beam with a duty factor  $\sim 100\%$ ;
- 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  $\sim 85\%$

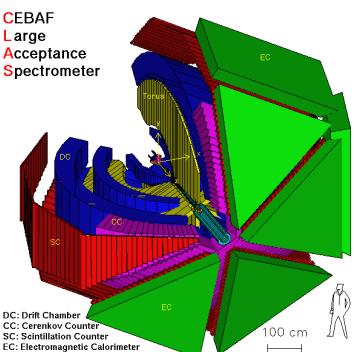


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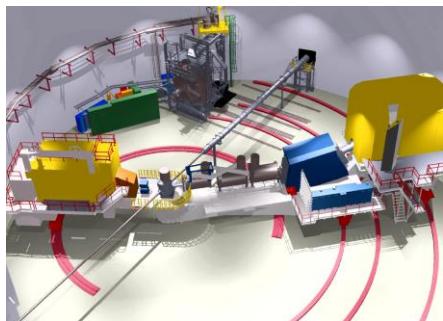
# The three experimental Halls@JLab



**Hall-A:** High-resolution spectrometers ( $\delta p/p \sim 10^{-4}$ ), measurements with well-defined kinematics at very high luminosity  
*NIM A 522, 294 (2004)*

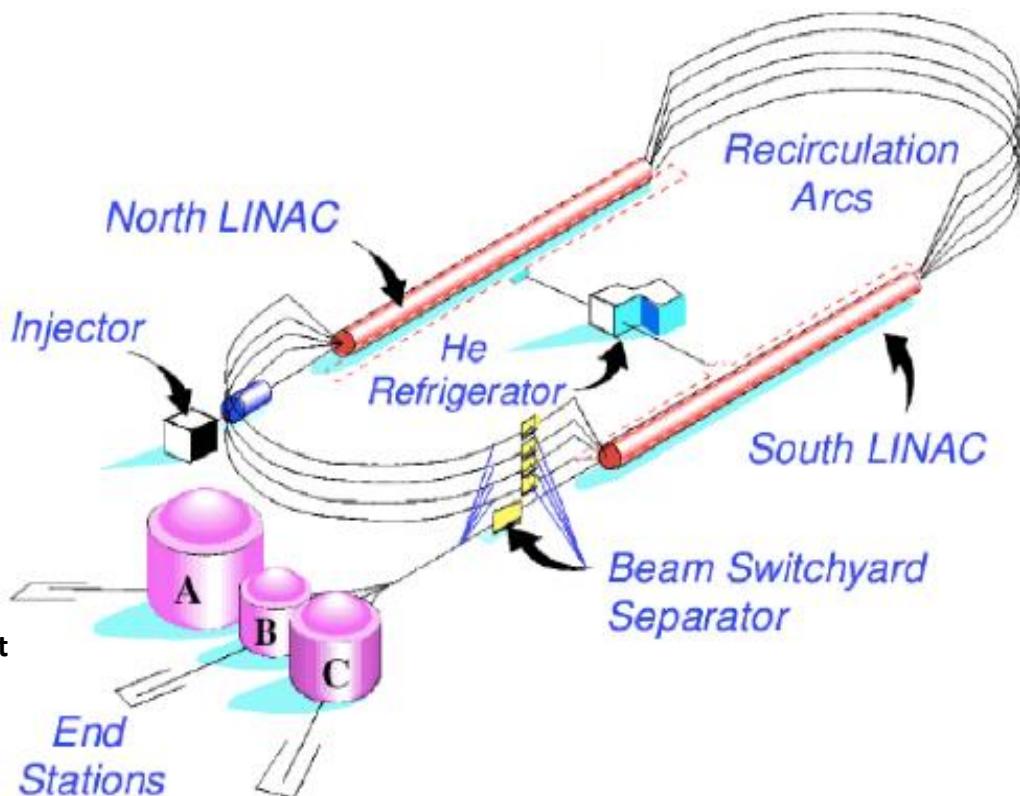


**Hall-B:** high luminosity, Large acceptance, Multi-particle final state measurements  
*NIM A 503, 513 (2003)*

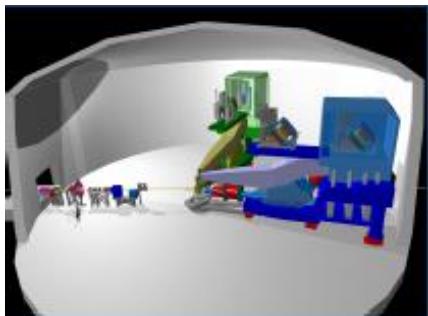


**Hall C:** High momentum spectrometer and Short Orbit Spectrometer—well-controlled acceptance for precise cross section measurements  
*PRC 78, 045202 (2008)*

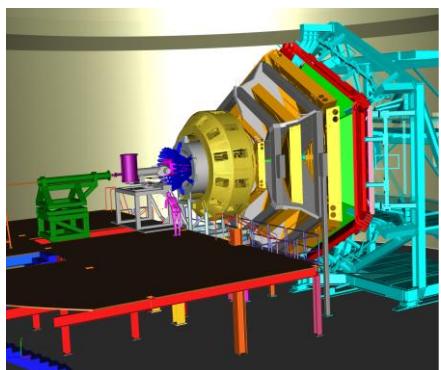
The CEBAF provides longitudinally-polarized electrons to 3 experimental Halls, characterized by different and complementary characteristics.



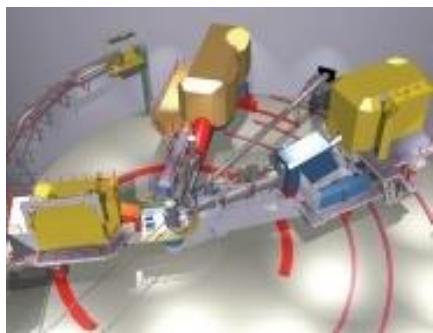
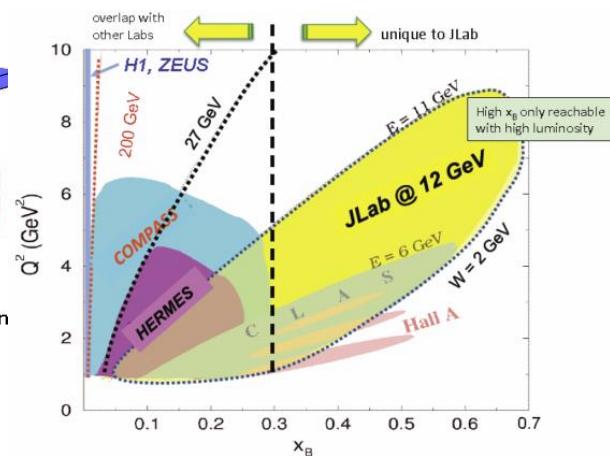
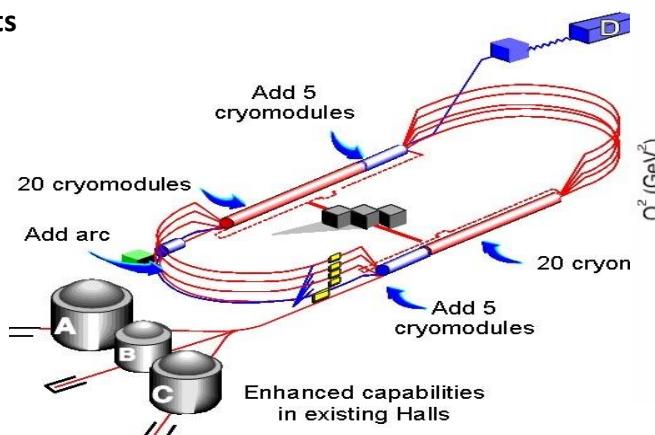
# The 12-GeV upgrade



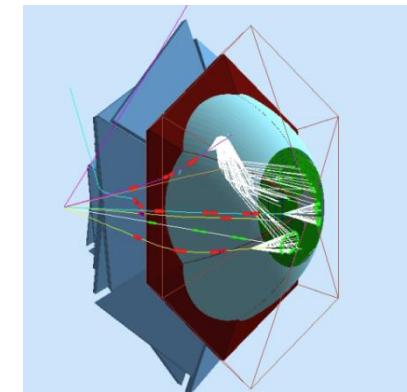
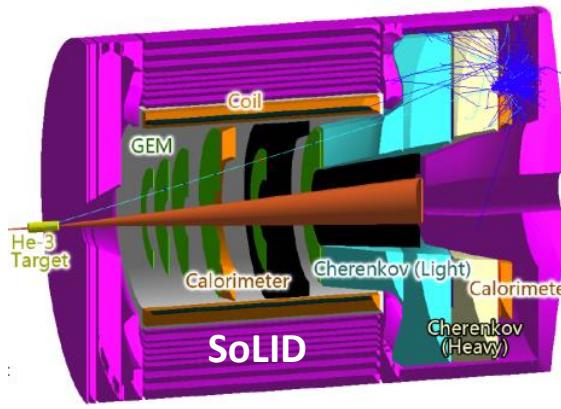
High Resolution  
Spectrometer  
(HRS) pair  
and specialized  
large installation  
experiments



CLAS12:  
large  
acceptance,  
high  
luminosity



Super High  
Momentum  
Spectrometer  
(SHMS)  
at high  
luminosity and  
forward angles



RICH for CLAS12

# Sensitivity to GPDs in observables - Compton Form Factors



Only  $(\xi, t)$  are experimentally accessible, not  $x$ . GPDs will enter in the observables through

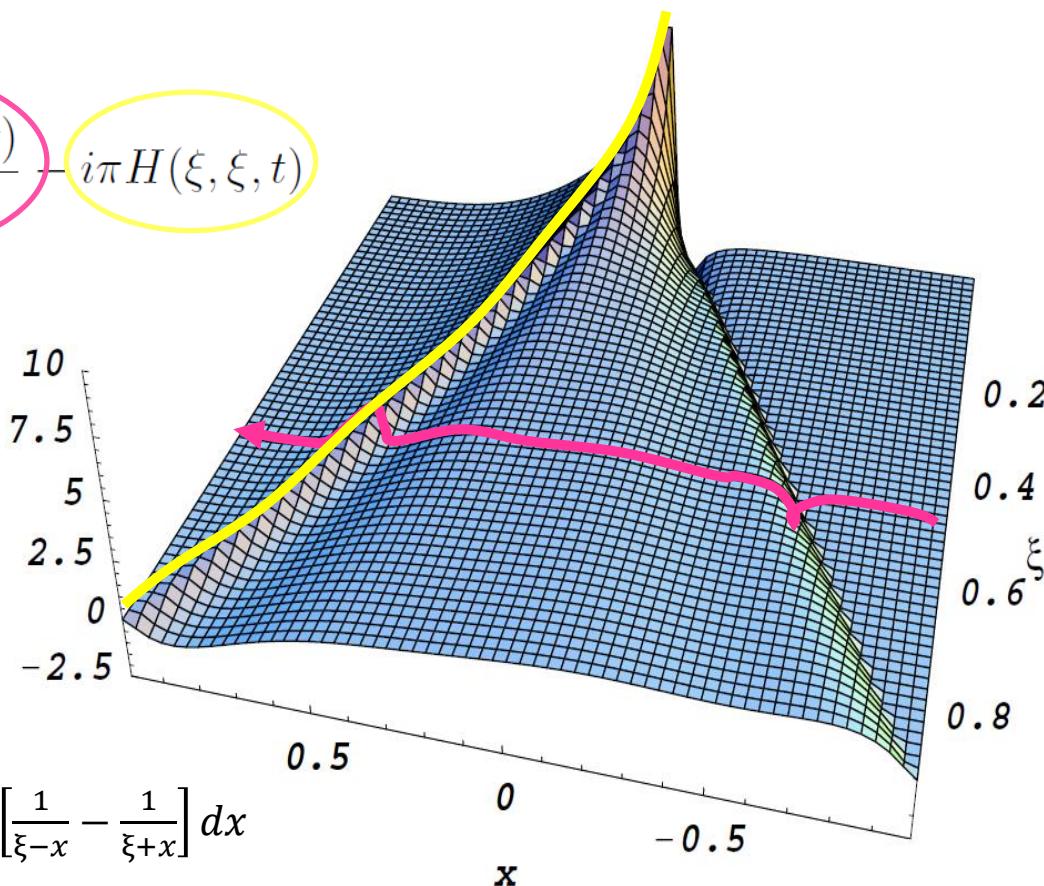
$$\int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi + i\epsilon} = \mathcal{P} \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi} + i\pi H(\xi, \xi, t)$$

The two parts will be accessible through observables sensible to the *imaginary* ( $A_{LU}, A_{UL}$ ) or the *real part* ( $A_{LL}, A_{BeamCharge}$ ) of the amplitude.

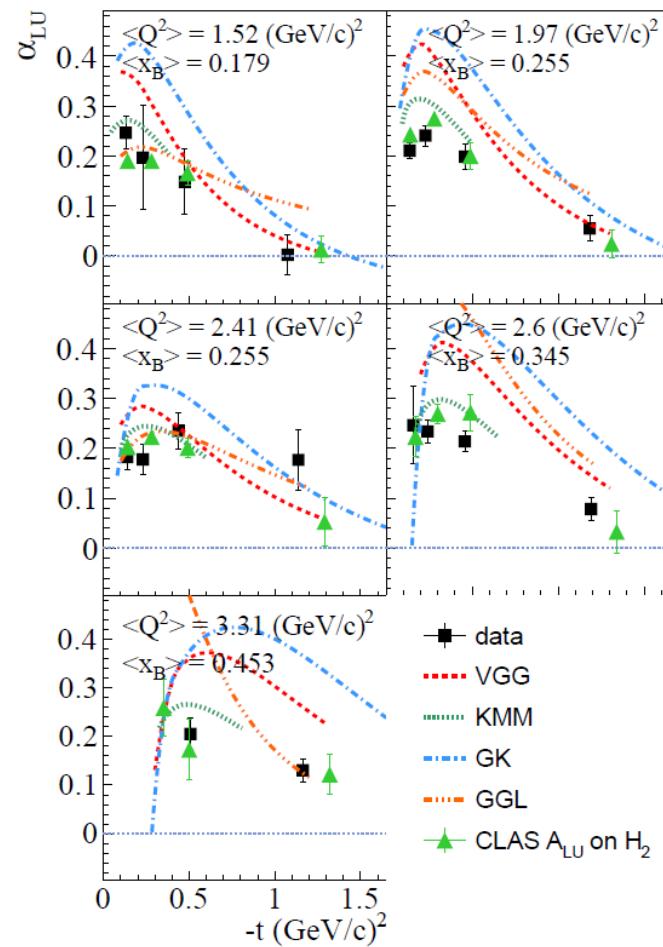
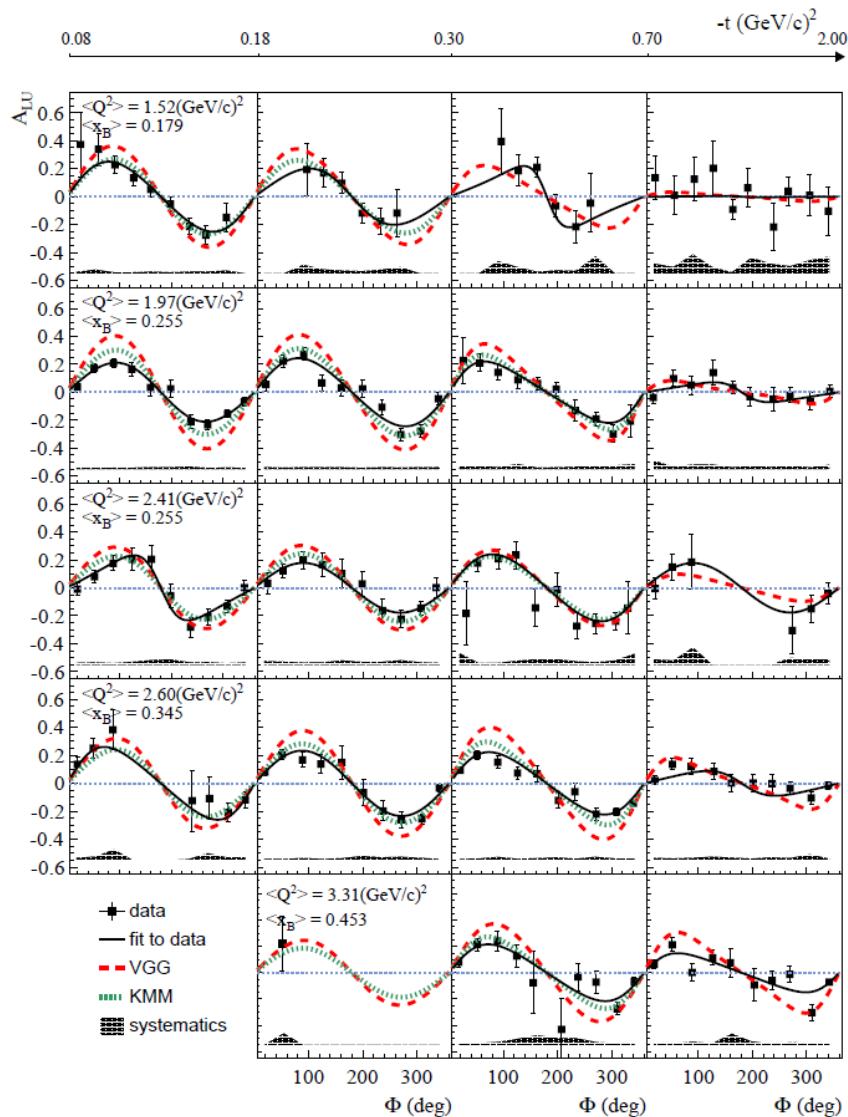
The following **Compton Form Factors** are introduced (experimentally observable):

$$Re\mathcal{H}_q = e^2 q P \int_0^1 (H^q(x, \xi, t) - H^q(-x, \xi, t)) \left[ \frac{1}{\xi-x} - \frac{1}{\xi+x} \right] dx$$

$$Im\mathcal{H}_q = \pi e^2 q (H^q(\xi, \xi, t) - H^q(-\xi, \xi, t))$$

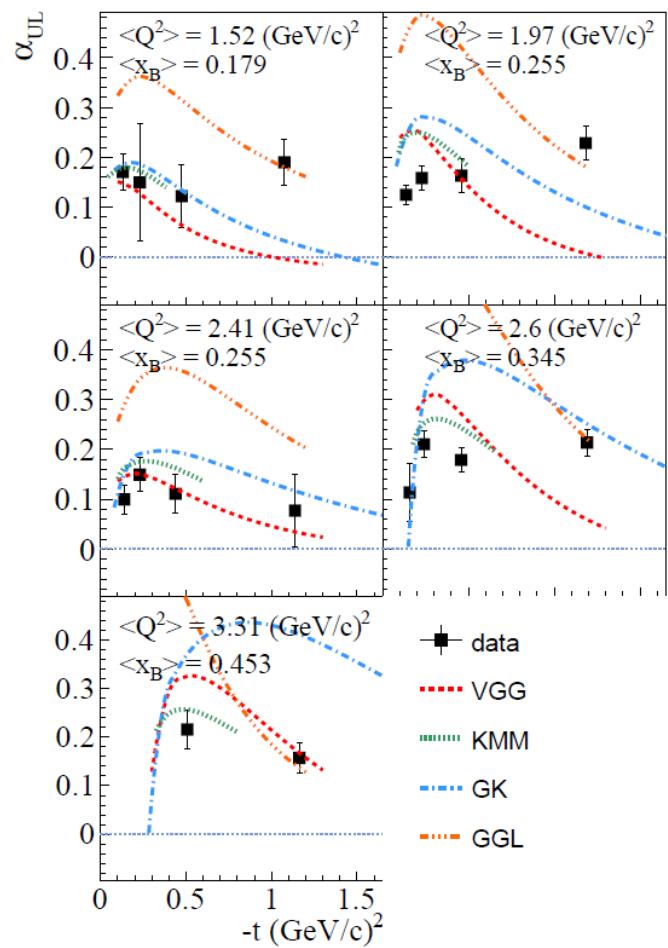
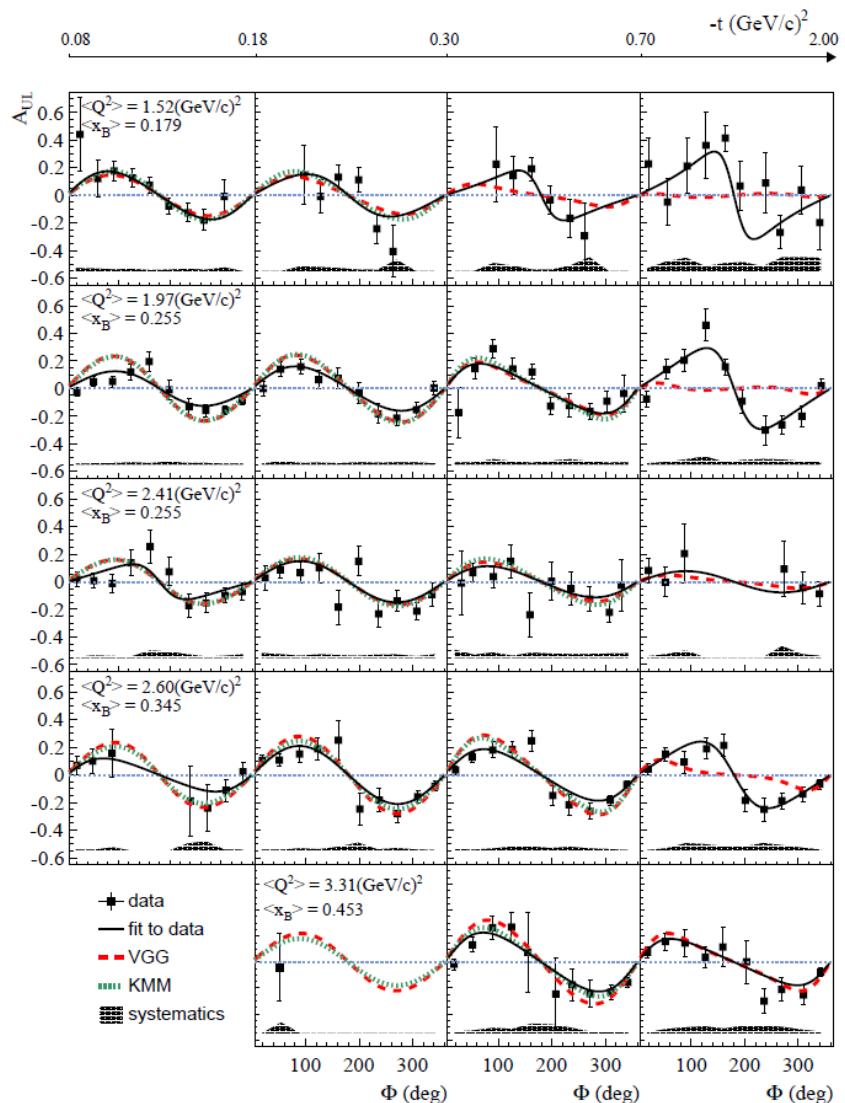


# $A_{LU}$ on $NH_3$



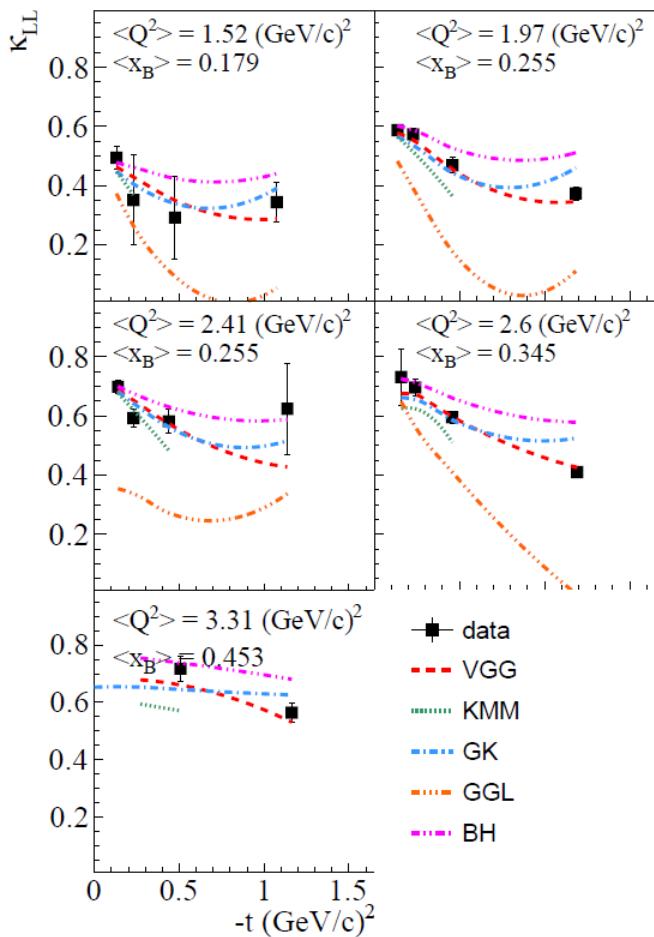
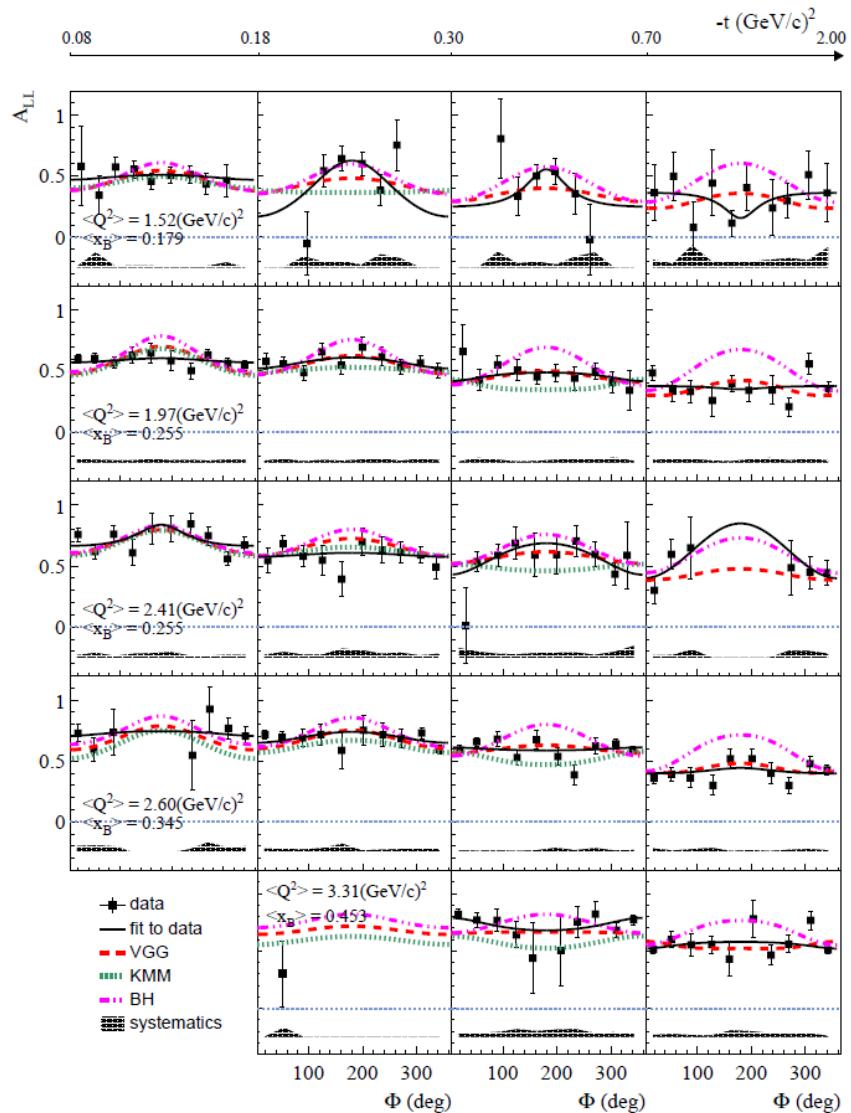
E. Seder et al, Phys. Rev. Lett. 114, 032001 (2015)  
 S.P. et al, arXiv:1501.07052 [hep-ex] – accepted by PRD

# $A_{UL}$ on $NH_3$



E. Seder et al, Phys. Rev. Lett. 114, 032001 (2015)  
 S.P. et al, arXiv:1501.07052 [hep-ex] – accepted by PRD

# $A_{LL}$ on $NH_3$



E. Seder et al, Phys. Rev. Lett. 114, 032001 (2015)  
 S.P. et al, arXiv:1501.07052 [hep-ex] – accepted by PRD

# Higher-twist PDF: E12-06-112B



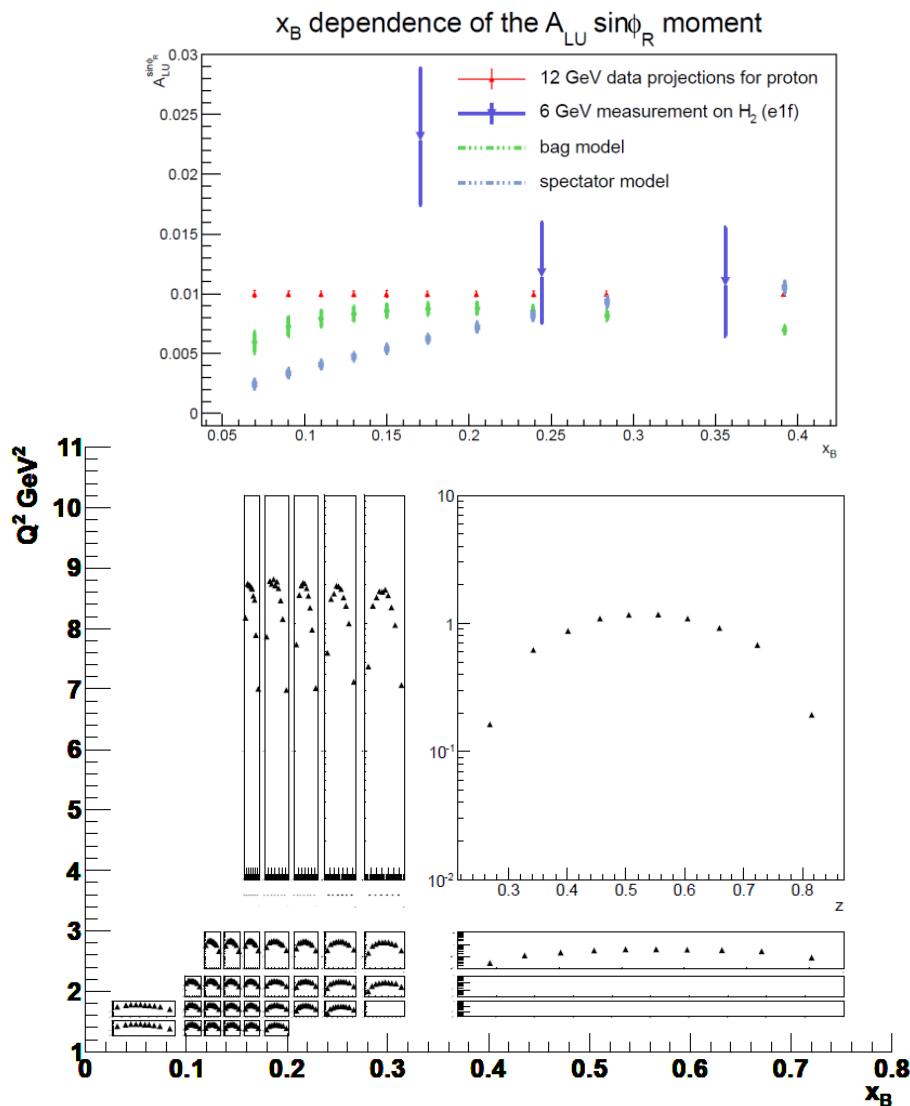
→ di-hadron SIDIS  $A_{LU}$  & Multiplicities on hydrogen and deuterium (56 days @  $\mathcal{L} = 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ )

→ access to the higher-twist PDF  $e(x)$

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

Also **unpolarized multiplicities** will be extracted in 10x10x10x5 ( $x_B, z, m_{\pi^+\pi^-}, Q^2$ ) bins

$$M^h(z, m_{\pi\pi}, x; Q^2) = \frac{\sum_q e_q^2 f_1^q(x; Q^2) D_1^q(z, m_{\pi\pi}; Q^2)}{\sum_q e_q^2 f_1^q(x; Q^2)}$$



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



$e(x)$  can also be extracted through di-hadron SIDIS  
 $A_{LU}$

→ cleaner access than in 1h SIDIS (no convolution)

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

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

extracted through Belle data

