JEFFERSON LAB HALL-B RESULTS

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INFN Ferrara

Spin Structure – EINN15
November 3, 2015 Paphos

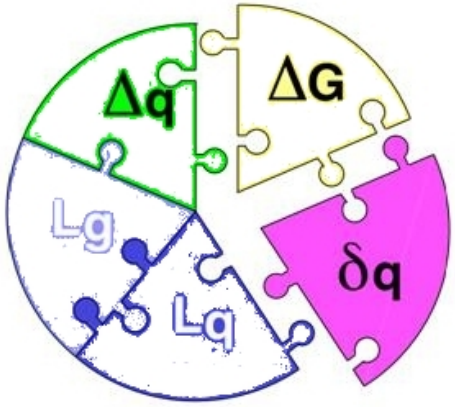
The Spin Degree of Freedom

In our exploration of the QCD micro-world

Fundamental: do not neglect spin !!

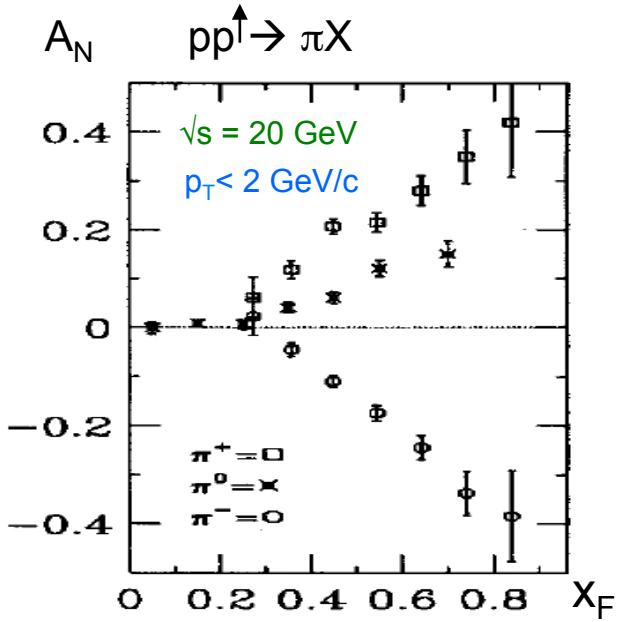
Two questions in Hadronic Physics
await explanation since too long

Proton Spin Budget

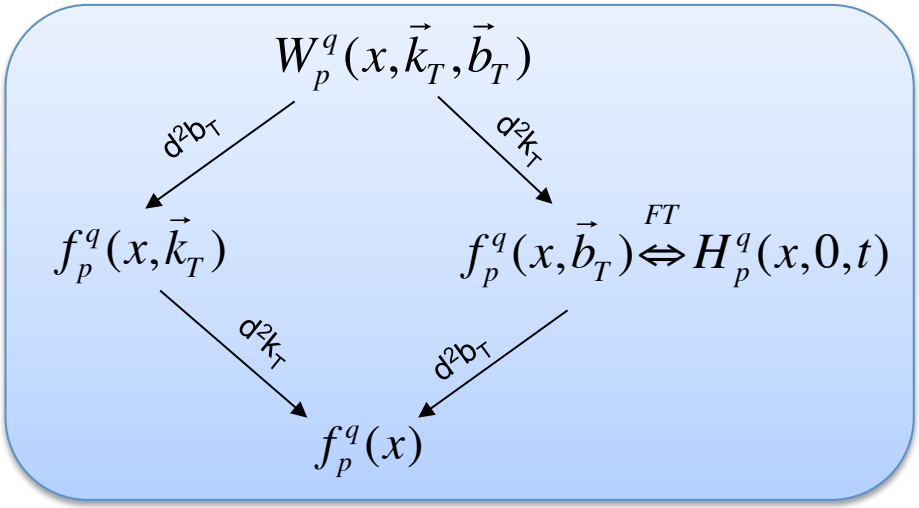


$$\frac{1}{2} = \frac{1}{2}\sum_f (q_f^+ - q_f^-) + L_q + \Delta G + L_g$$

Single Spin Asymmetries



The 3D Nucleon Structure



Confinement Scale

Transverse momentum

$\vec{k}_T$

$\vec{b}_T$

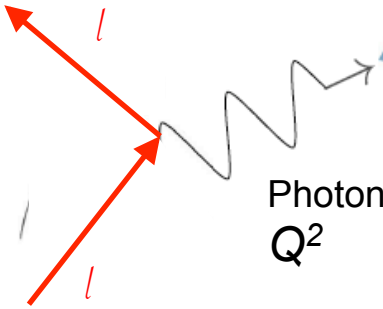
Transverse position

High Energy Probe
Hard Scale

Longitudinal momentum
$k^+ = xP^+$

Spin

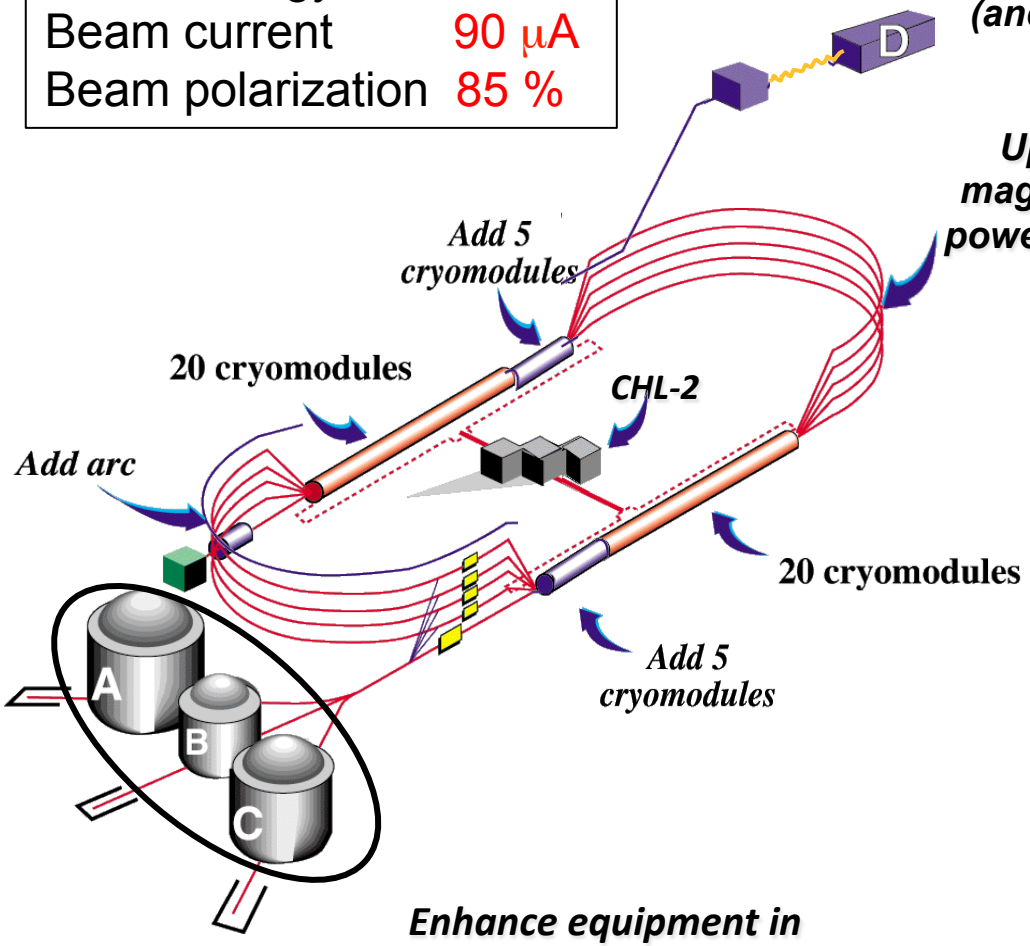
Transverse plane



Photon Virtuality
Q^2

CEBAF Upgrade at Jefferson Lab

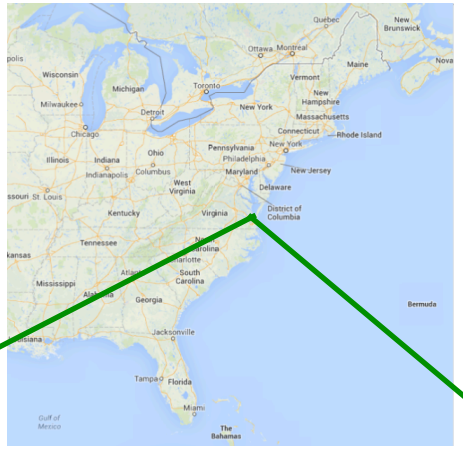
Beam Energy	12 GeV
Beam current	90 μA
Beam polarization	85 %



add Hall D (and beam line)

Upgrade magnets and power supplies

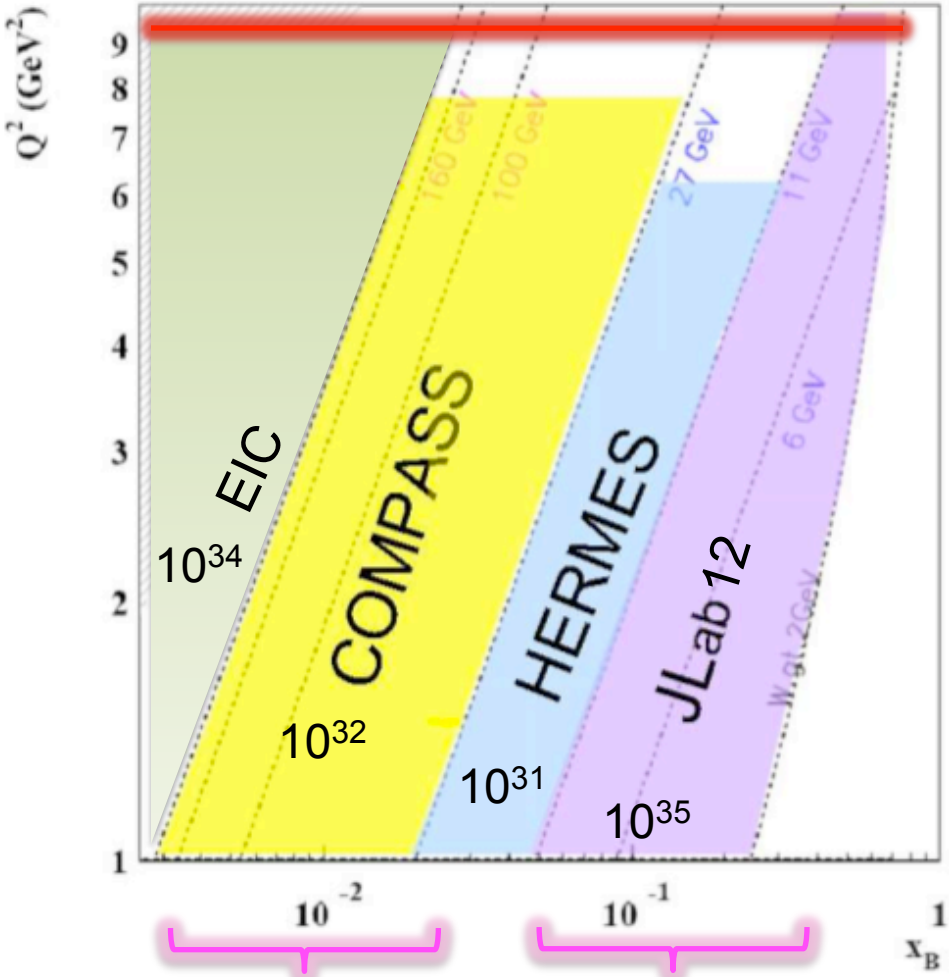
Enhance equipment in existing halls



Beam is being delivered to the Halls

The SIDIS Landscape

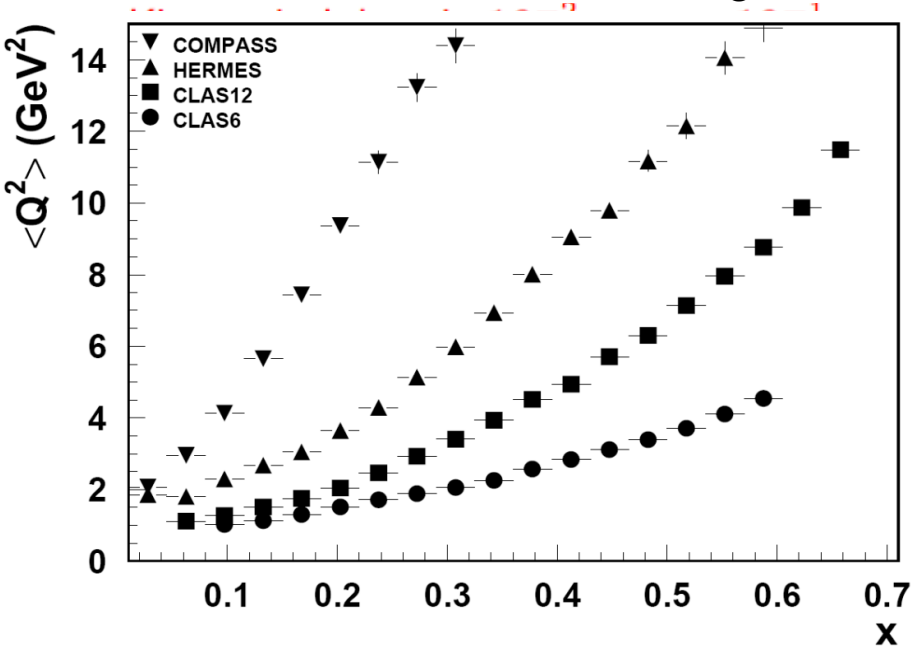
Limit defined by luminosity



Sea

Valence

Different Q^2 for same x range



Complementary experiments

Hall-B Mission

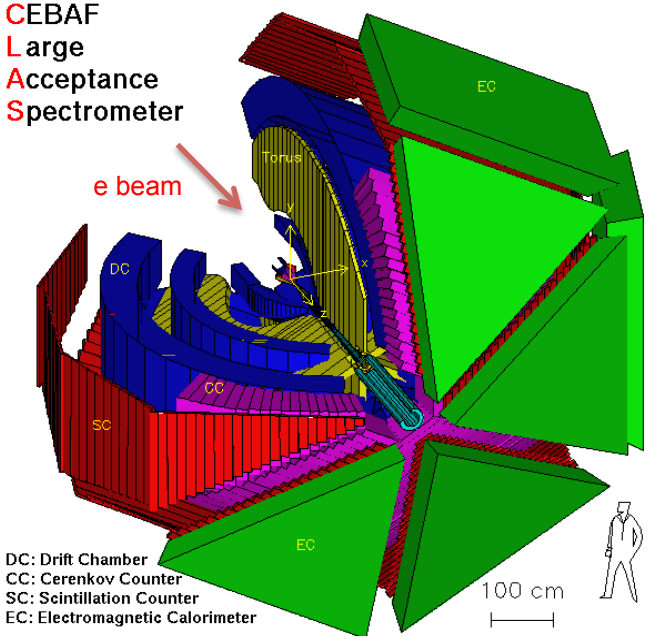
Comprehensive measurements based on :

- High luminosity up to 10^{35} cm^{-2} s^{-1}
- Large acceptance (current & target fragmentation)
- Polarized beam and targets
- Multi-particle final state measurements

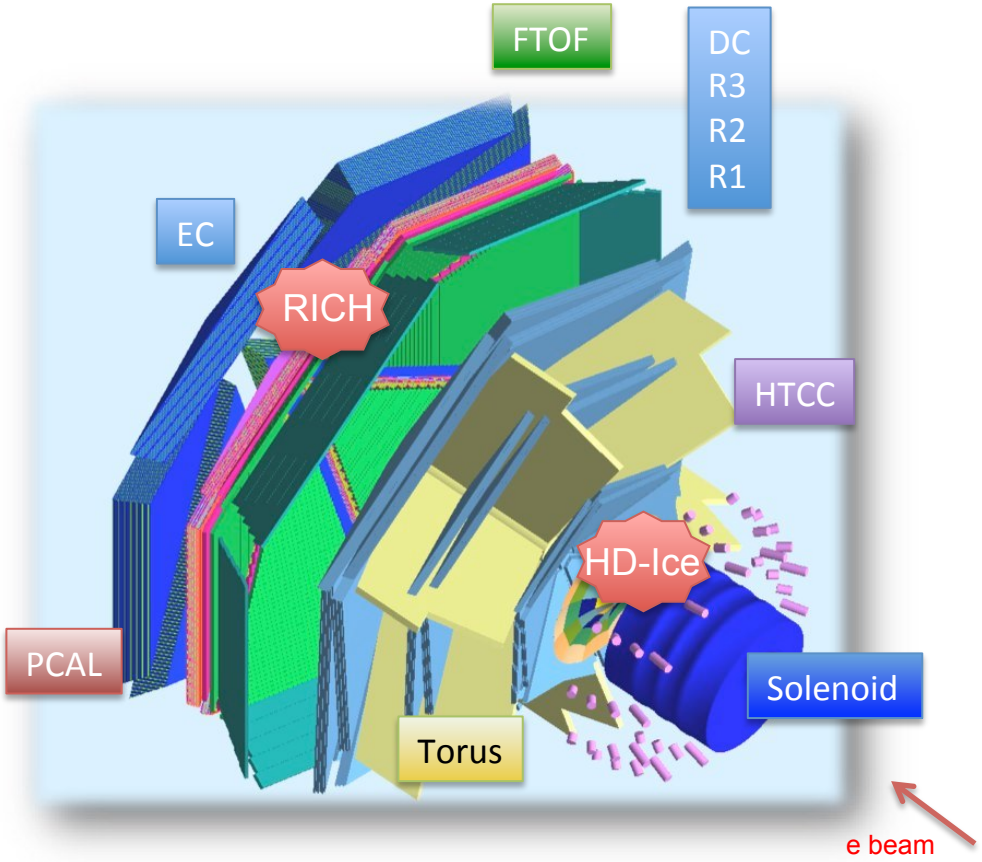
6 GeV

NIM A503, 513 (2003)

CEBAF
Large
Acceptance
Spectrometer



12 GeV



The 3D Nucleon Structure

$W_p^q(x,\vec{k}_T,\vec{b}_T)$

d^2b_T

$f_p^q(x,\vec{k}_T)$

d^2k_T

$f_p^q(x)$

Confinement Scale

Transverse momentum

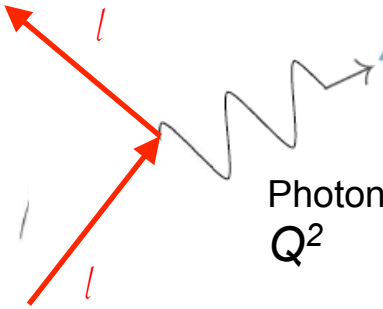
$\vec{k}_T$

High Energy Probe
Hard Scale

Longitudinal momentum
$k^+=xP^+$

Spin

Transverse plane

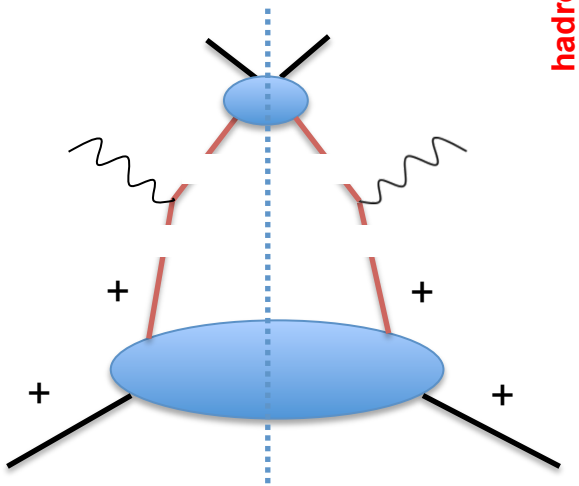


Photon Virtuality
Q^2

DIS Cross-Section

From optical theorem:
related to the imaginary part of the forward scattering

TMD Factorization holds for $p_T << Q$



Hard scattering

Quark-quark correlator

Quark fragmentation

hadron polarisation \ quark polarisation	N/q	U	L	T
	U	D_1		$H_1^\perp$

$$\Phi_{ij}(P,S;p) = \frac{1}{(2\pi)^4}\int d^4x\; e^{i\,p\cdot x}\langle P,S|\overline{\psi}_j(0)\mathcal{L}(0,x;\text{path})\psi_i(x)|P,S\rangle$$

Projection into
8 Lorentz structures

$$\Phi^{[\Gamma]}(x,\boldsymbol{p}_T) = \frac{1}{2}\int dp^-\; Tr(\Phi\,\Gamma)\Big|_{p^+=xP^+,\;\boldsymbol{p}_T}$$

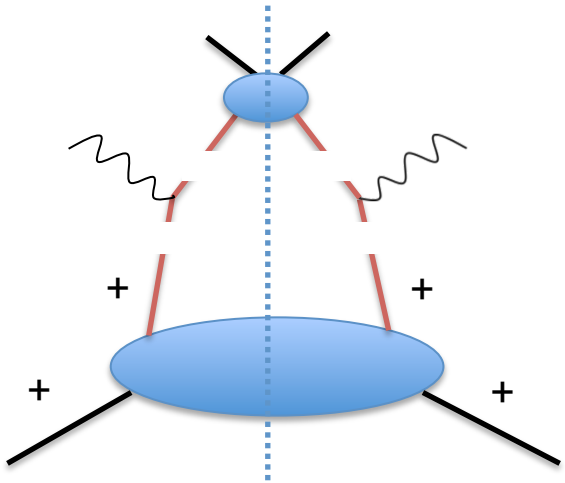
nucleon polarisation \ quark polarisation	N/q	U	L	T
	U	f_1		$\boldsymbol{h}_1^\perp$
	L		g_1	$\boldsymbol{h}_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1, h_{1T}^\perp$

DIS Cross-Section

Wide kinematic coverage is needed to resolve the convolution

$$F_{UU} = f \otimes D = x \sum_q e_q^2 \int d^2 p_T d^2 k_T \;\; \delta^{(2)}(\mathbf{P}_{h\perp} - z\mathbf{k}_T - \mathbf{p}_T) \;\; w(\mathbf{k}_T, \mathbf{p}_T) \;\; f^q(x, k_T^2) \;\; D^q(z, p_T^2)$$

TMD Factorization holds for $p_T \ll Q$



Quark fragmentation

Hard scattering

Quark-quark correlator

$$\frac{d^6\sigma}{dx dQ^2 dz dP_h d\phi d\phi_S} \overset{LT}{\propto} \left[F_{UU} + \varepsilon \cos(2\phi) F_{UU}^{\cos(2\phi)} \right] + S_L \left[\varepsilon \sin(2\phi) F_{UL}^{\sin(2\phi)} \right]$$

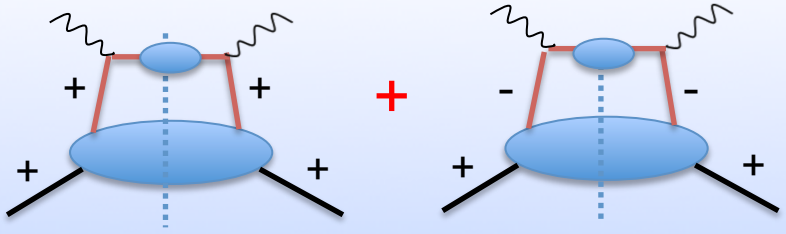
$$+ S_T \left[\sin(\phi - \phi_S) F_{UT}^{\sin(\phi-\phi_S)} + \varepsilon \sin(\phi + \phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon \sin(3\phi - \phi_S) F_{UT}^{\sin(3\phi-\phi_S)} \right]$$

$$+ S_L \lambda_e \left[\sqrt{1-\varepsilon^2} F_{LL} \right] + S_T \lambda_e \left[\sqrt{1-\varepsilon^2} \cos(\phi - \phi_S) F_{LT}^{\cos(\phi-\phi_S)} \right] + O\left(\frac{1}{Q}\right)$$

Unpolarized TMDs

$\Phi[\gamma^+]$

$$f_1(x) = q^+(x) + q^-(x)$$



quark polarisation

nucleon polarisation

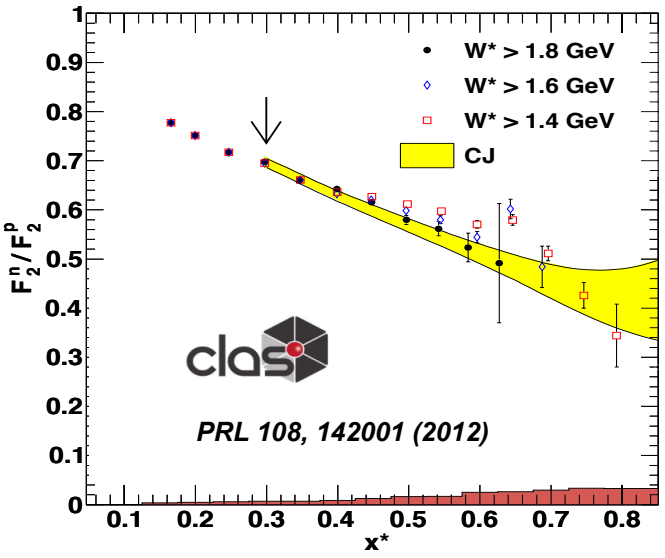
N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1, h_{1T}^\perp$

quark polarisation

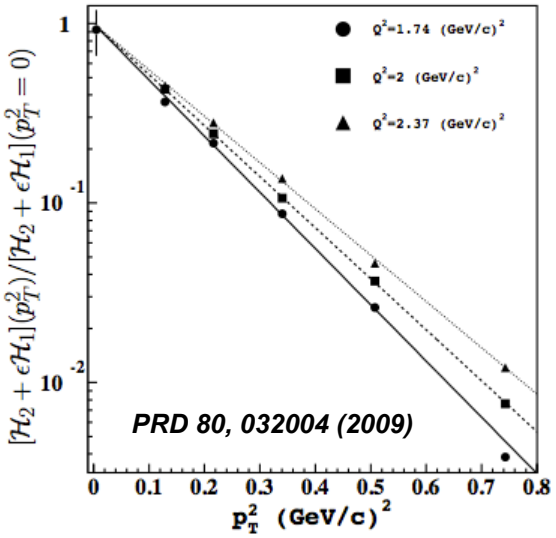
hadron polarisation

N/q	U	L	T
U	D_1		$H_1^\perp$

Scattering on deuterium with proton spectator tagging



Extending the study to the transverse momentum

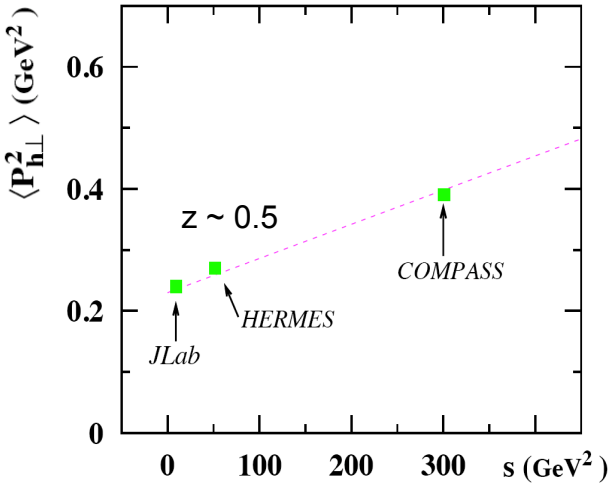


TMD Evolution

TMD evolution:

k_T and p_T broadening with c.m. energy

P. Schweitzer++ [arXiv:1003.2190]



TMD Q^2 evolution

≠

DGLAP

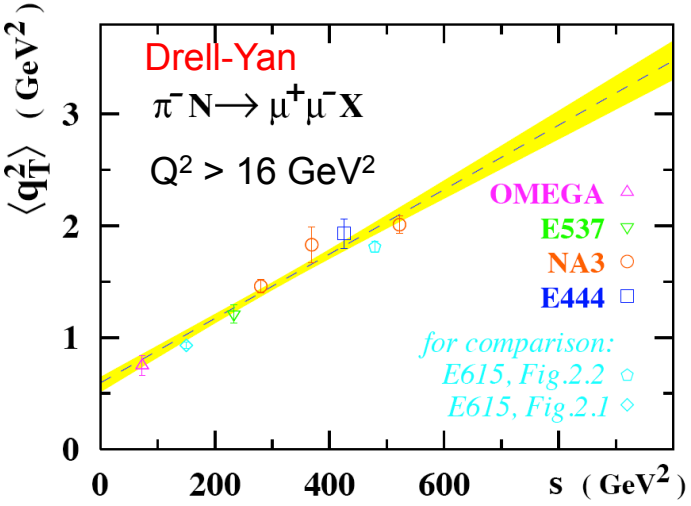
Fixed target SIDIS

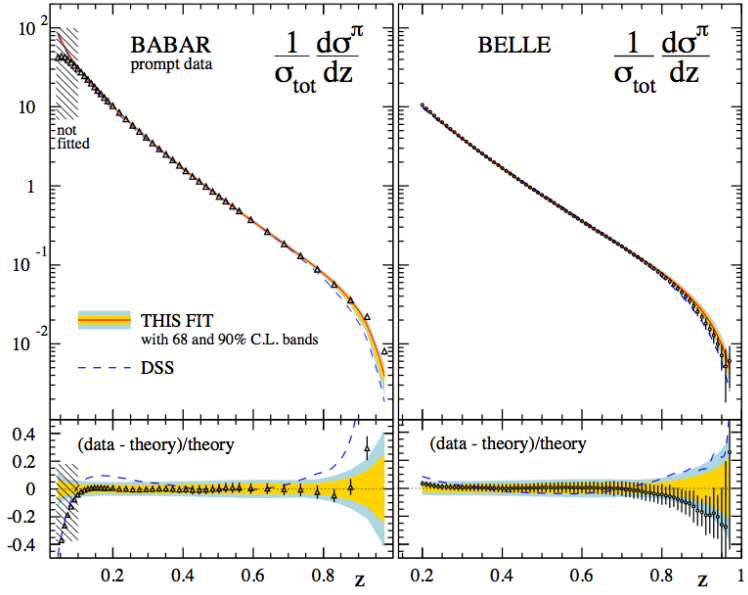
Q^2 ~ few GeV^2

B-factories

Q^2 ~ 100 GeV^2

Still collinear

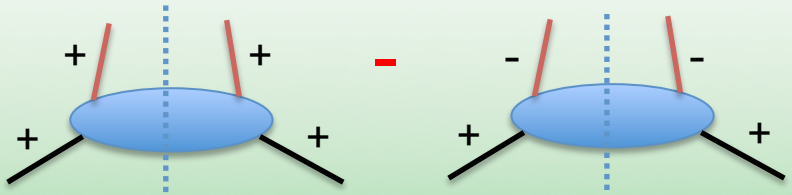


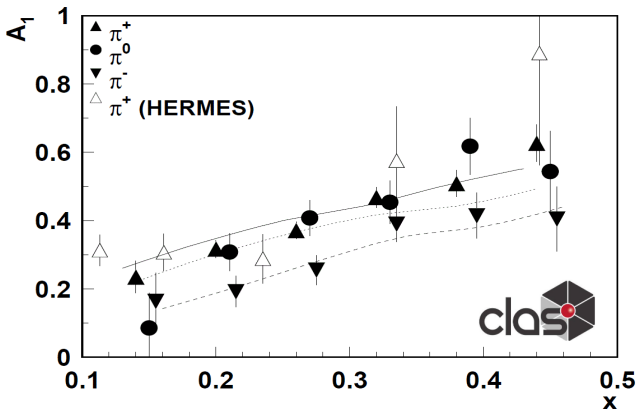


Quark Helicity

$\Phi[\gamma^+\gamma^5]$

$$g_1(x) = q^+(x) - q^-(x)$$





High-statistics (x10) on 2009 data in progress

quark polarisation

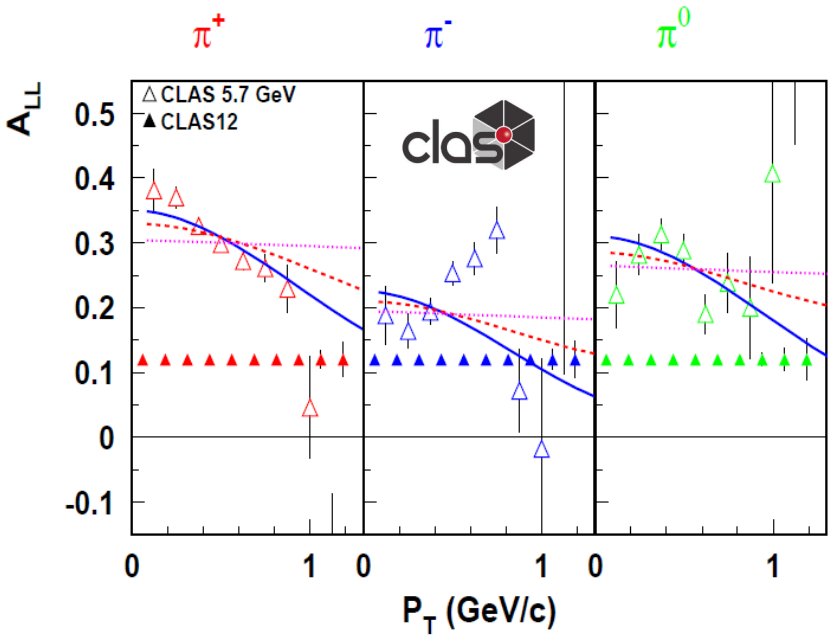
nucleon polarisation

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

quark polarisation

hadron polarisation

N/q	U	L	T
U	D_1		$H_1^\perp$

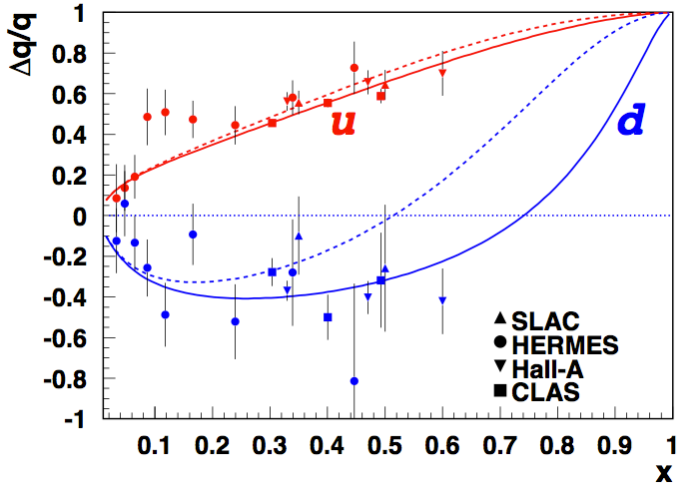


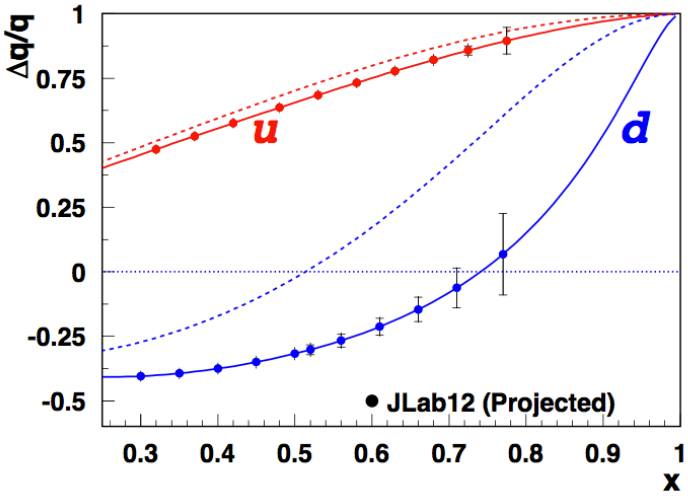
H. Avakian et al. PRL 105: 262002 (2010) [arXiv 1003.4549]

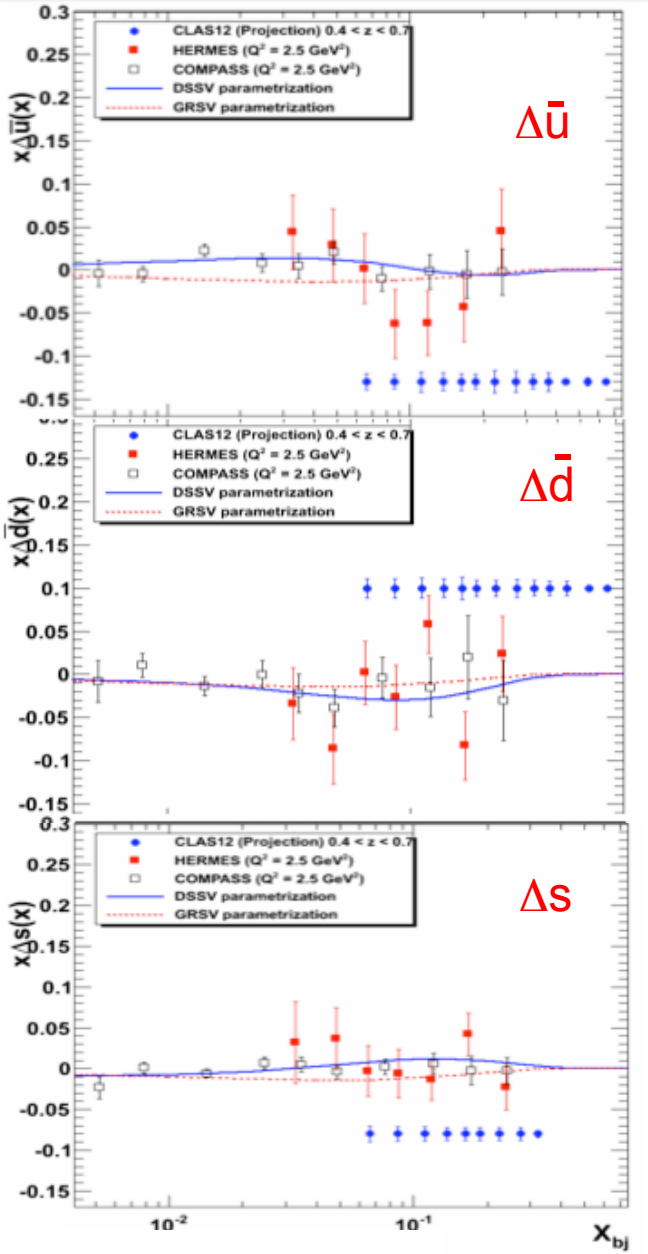
H. Avakian et al. E12-07-107 @ 12 GeV

Quark Helicity

$$\frac{1}{2} = \frac{1}{2}\sum_f (q_f^+ - q_f^-) + L_q + \Delta G + L_g$$





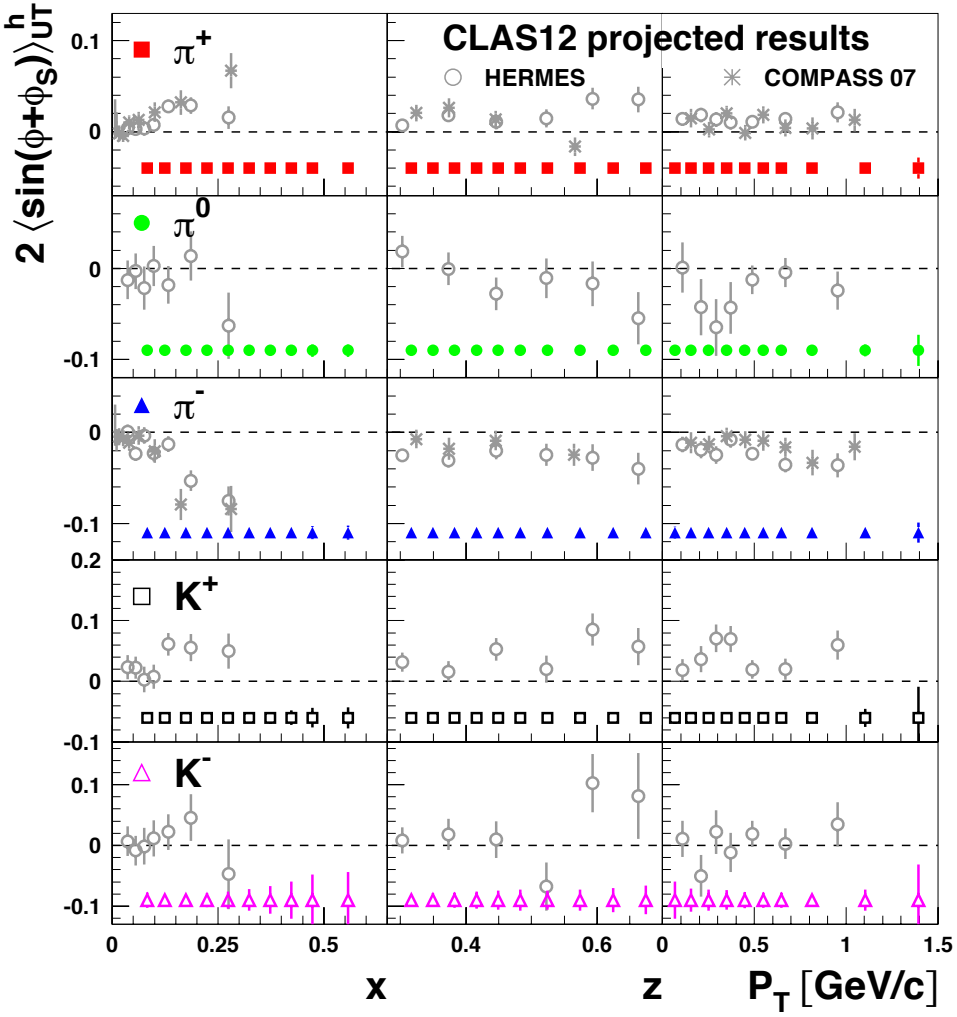


@CLAS12

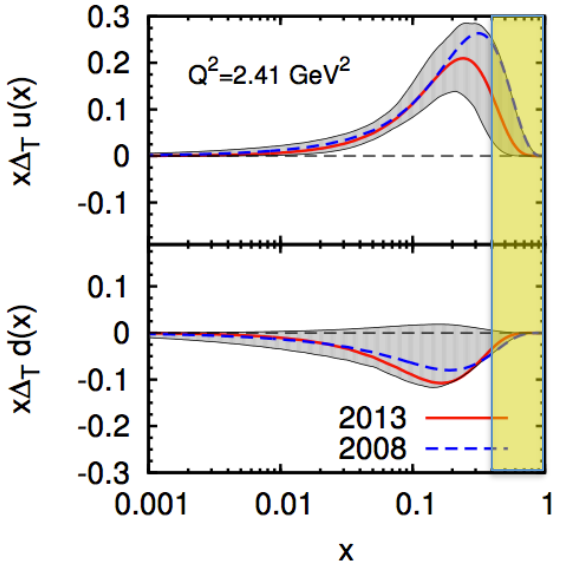
Transversity @ CLAS12

$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 \otimes H_1^{\perp}$$

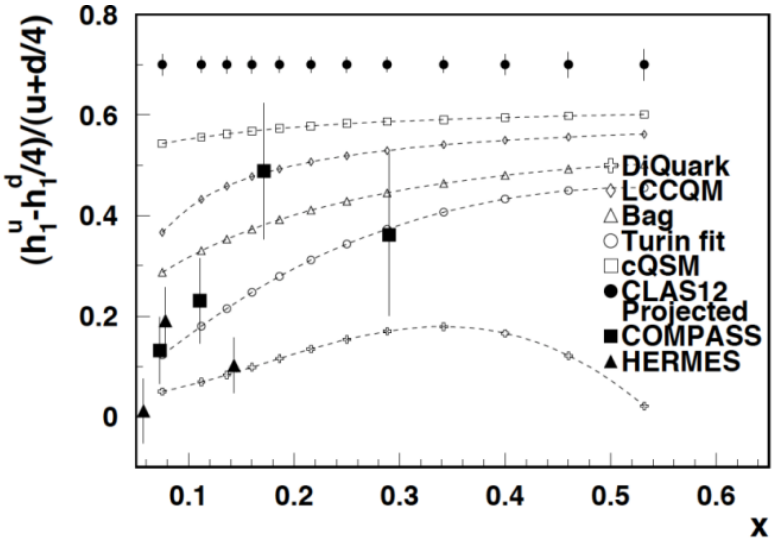
Single hadron channel: C12-11-111 Hall-B



Distributions:



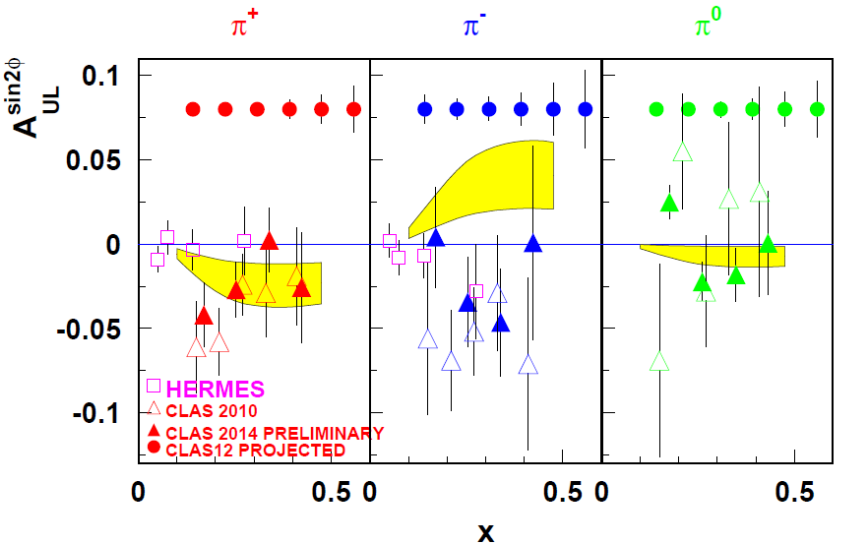
Di-hadron channel:



Spin-Orbit Correlations @ CLAS

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

First indication of non-zero $A_{UL}^{\sin\varphi}$ for pions
Potentially significant quark spin-orbit correlations



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

quark polarisation

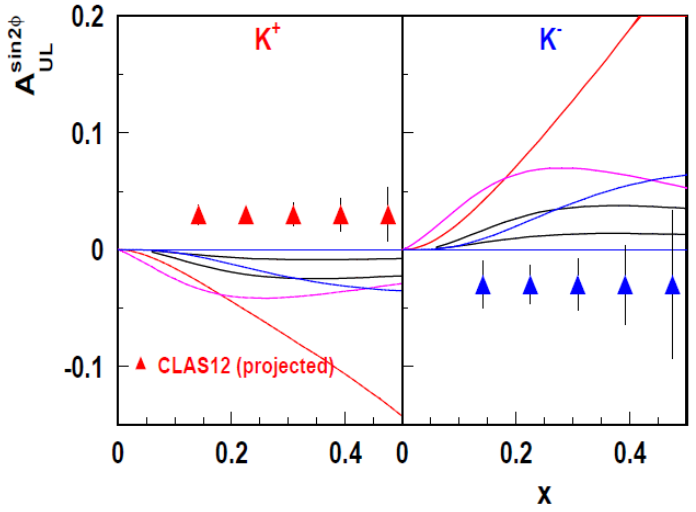
nucleon polarisation

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

quark polarisation

hadron polarisation

N/q	U	L	T
U	D_1		$H_1^{\perp}$



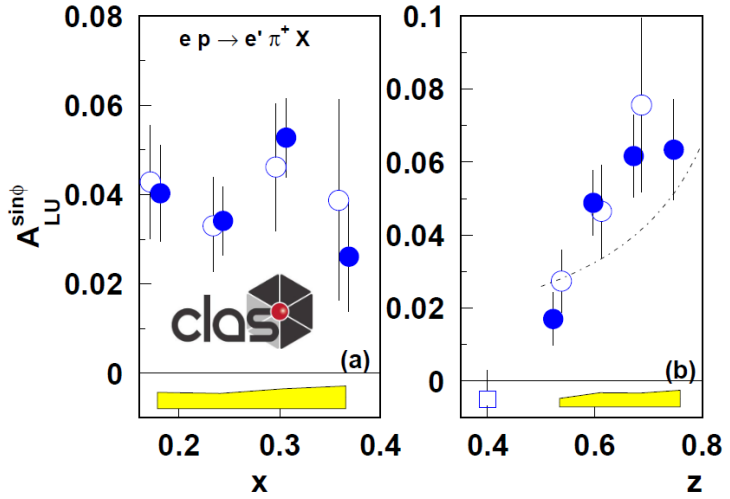
Higher-twists @ CLAS

A_{LU} is proportional to the structure function

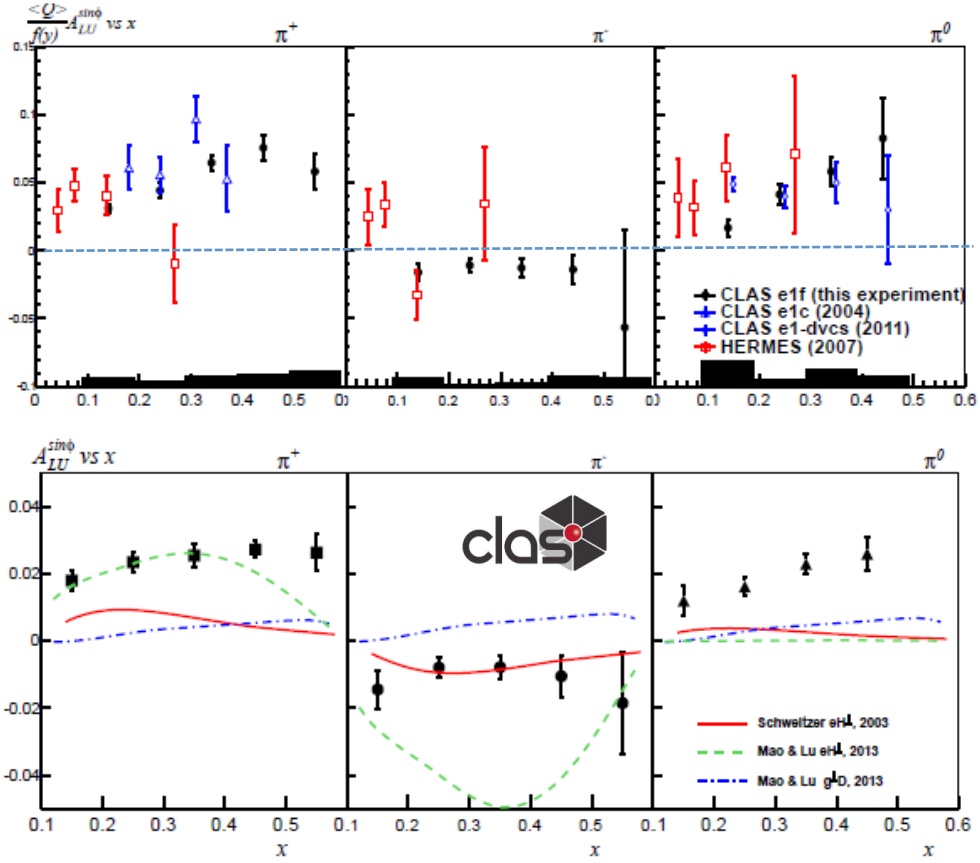
$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^{\perp}+\frac{M_h}{M}f_1\frac{\tilde{G}^{\perp}}{z}\right)+\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^{\perp}D_1+\frac{M_h}{M}h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

e(x): twist-3 PDF sensitive to qGq correlations "transverse force"

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



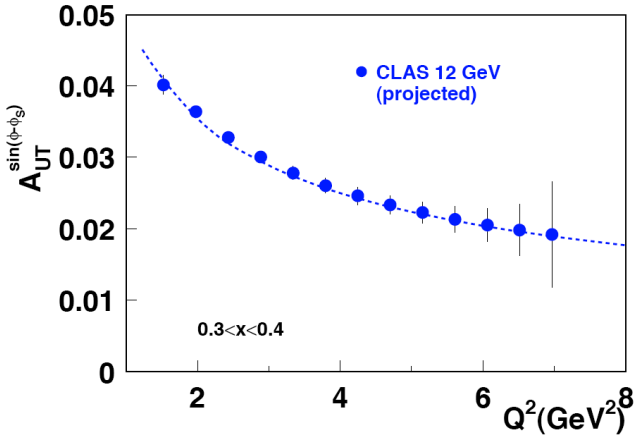
→ **Entire structure function is twist-3, so in commonly used Wandzura-Wilczek approximation entire asymmetry = 0**



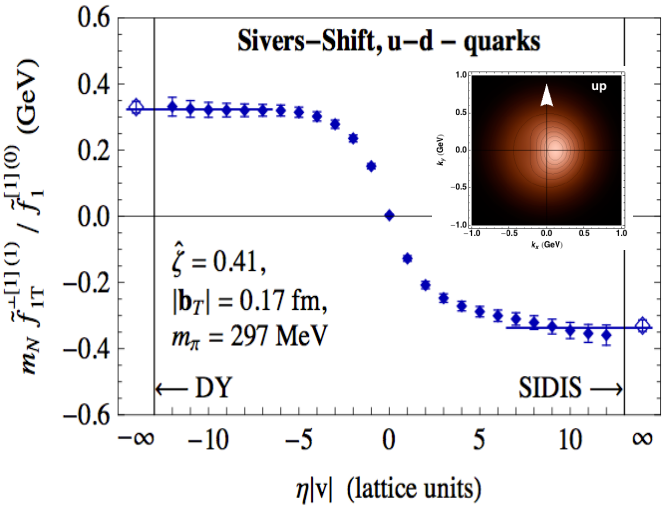
W. Gohn *et al.*, PRD89, 072011 (2014)@5.5 GeV

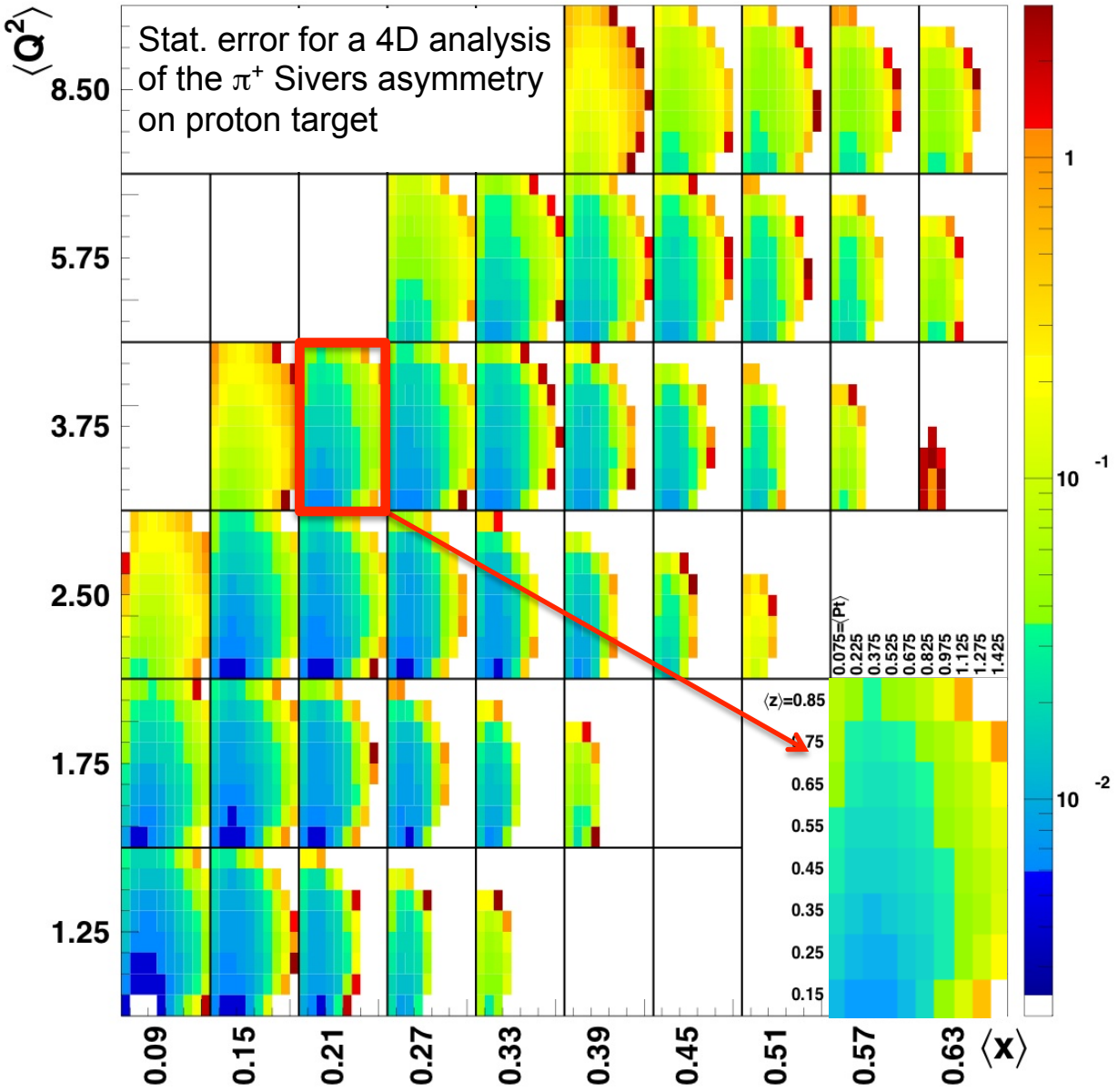
Sivers Mapping @ CLAS12

$$\sigma_{UT}^{\sin(\phi-\phi_S)} \propto f_{1T}^{\perp} \otimes D_1$$



Lattice $\langle k_\perp \rangle$





The 3D Nucleon Structure

$W_p^q(x,\vec{k}_T,\vec{b}_T)$

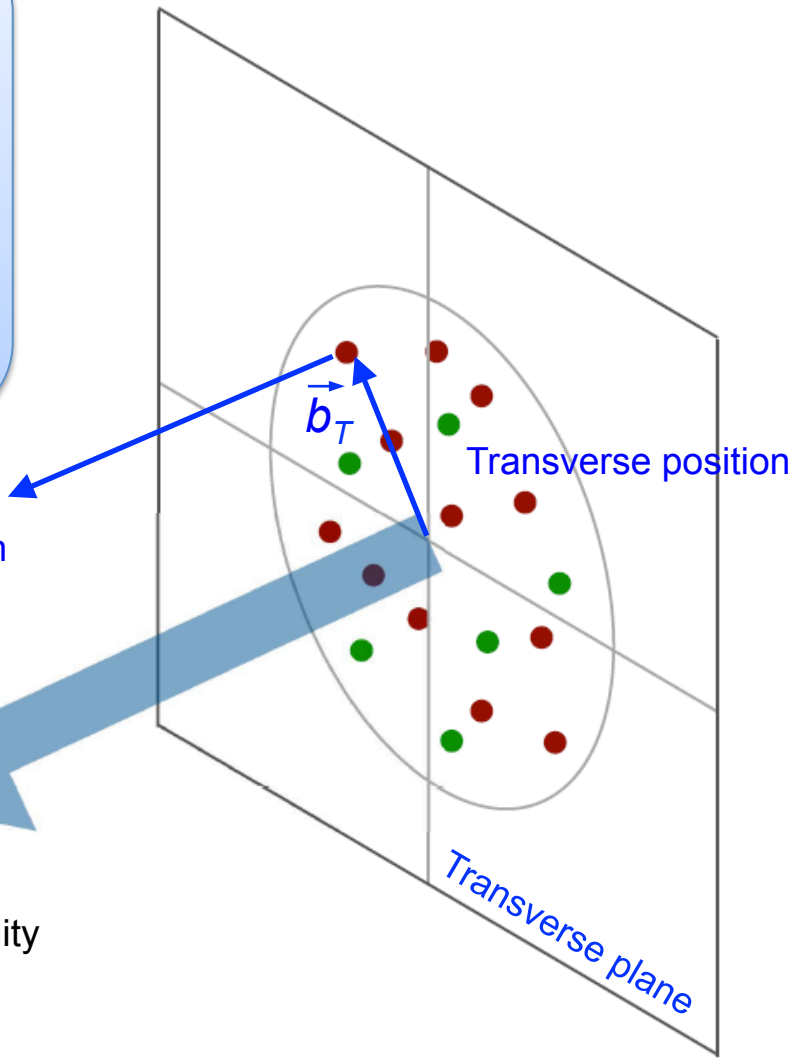
$\int d^2k_T$

$f_p^q(x,\vec{b}_T) \overset{FT}{\Leftrightarrow} H_p^q(x,0,t)$

$\int d^2b_T$ $\qquad$ $\int dx$

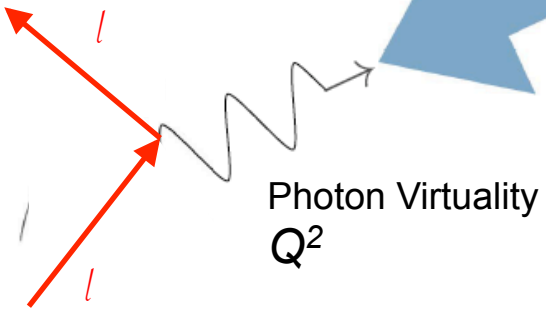
$f_p^q(x)$ $\qquad$ FF

Confinement Scale



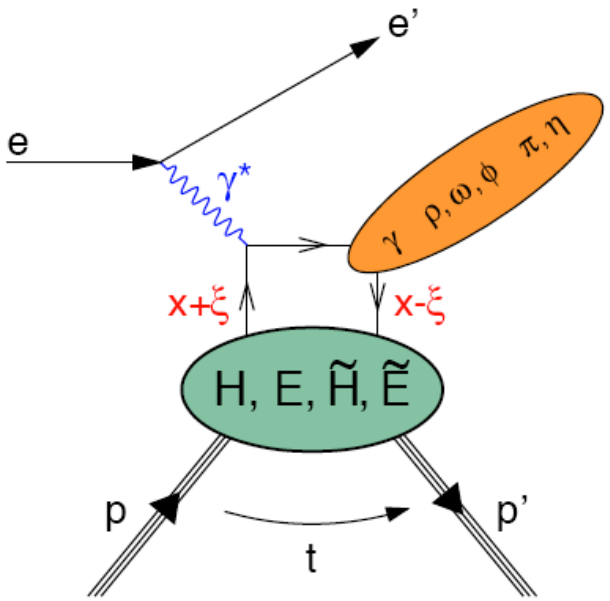
High Energy Probe
Hard Scale

Longitudinal momentum
$k^+ = xP^+$



Generalized parton distributions

Exclusive reaction:



- For spin-1/2 target 4 chiral-even leading-twist quark GPDs: $H, E, \tilde{H}, \tilde{E}$
- $H, \tilde{H}$ conserve nucleon helicity, $E, \tilde{E}$ involve nucleon helicity flip
- Sensitivity of different final states to different GPDs
- DVCS (γ) → $H, E, \tilde{H}, \tilde{E}$
- Vector mesons (ρ, ω, ϕ) → H, E
- Pseudoscalar mesons (π, η) → $\tilde{H}, \tilde{E}$

Access OAM $L_q = J_q - \frac{1}{2}\Delta\Sigma$ via Ji sum rule

$$\mathcal{J}_q = \lim_{t\to 0} \int_{-1}^{1} dx\, x\left[H_q(x,\xi,t) + E_q(x,\xi,t)\right]$$

Collinear PDFs as forward limit:

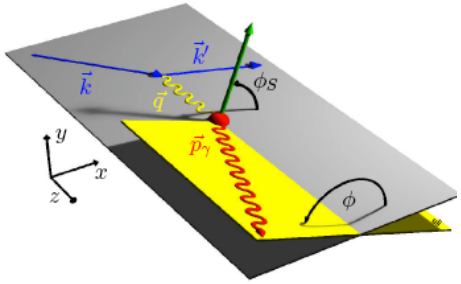
$$\int d^2 b_T H(x, b_T) = f_1(x)$$

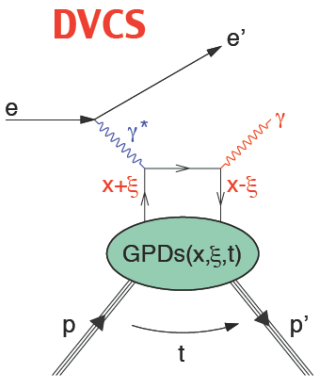
$$\int d^2 b_T \tilde{H}(x, b_T) = g_1(x)$$

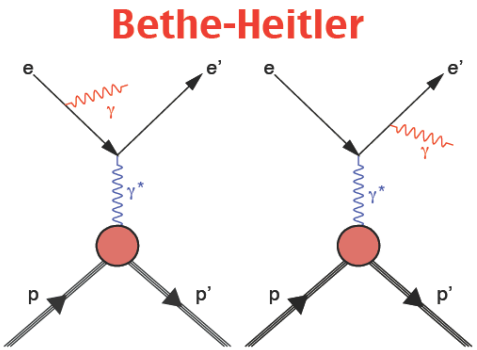
DVCS Interference

Informations on the real and imaginary part of the QCD scattering amplitude

$$\frac{d^4\sigma}{dQ^2\, dx_B\, dt\, d\phi} \propto \left(|\mathcal{T}_{\mathrm{DVCS}}|^2 + |\mathcal{T}_{\mathrm{BH}}|^2 + \mathcal{I}\right)$$



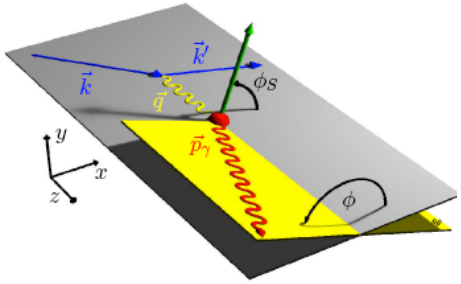




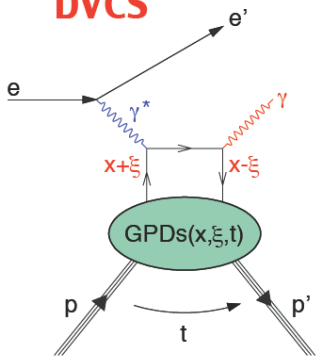
DVCS Interference

Informations on the real and imaginary part of the QCD scattering amplitude

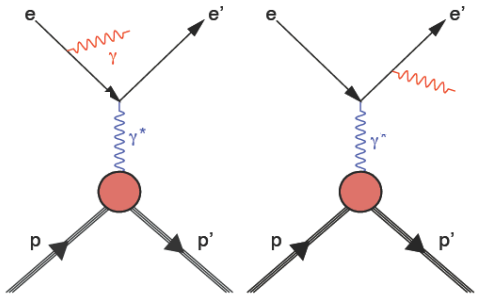
$$\frac{d^4\sigma}{dQ^2\,dx_B\,dt\,d\phi} \propto \left(|\mathcal{T}_{DVCS}|^2 + |\mathcal{T}_{BH}|^2 + \mathcal{I}\right)$$



DVCS

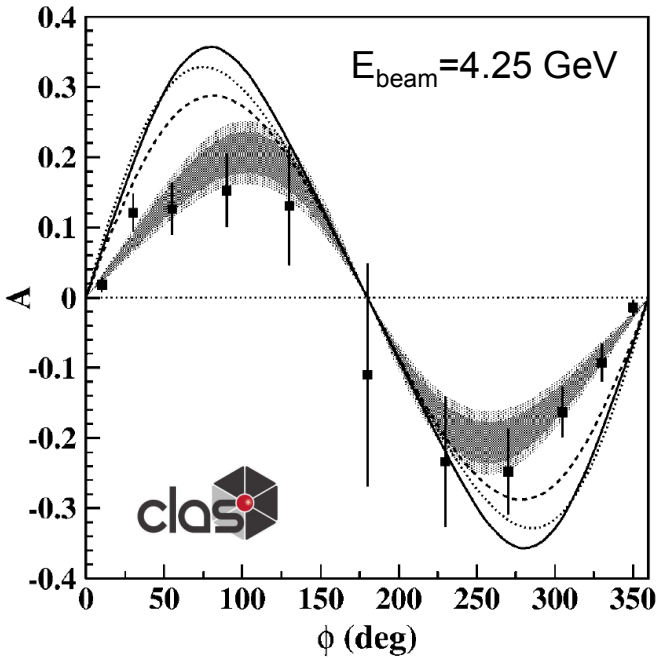


Bethe-Heitler



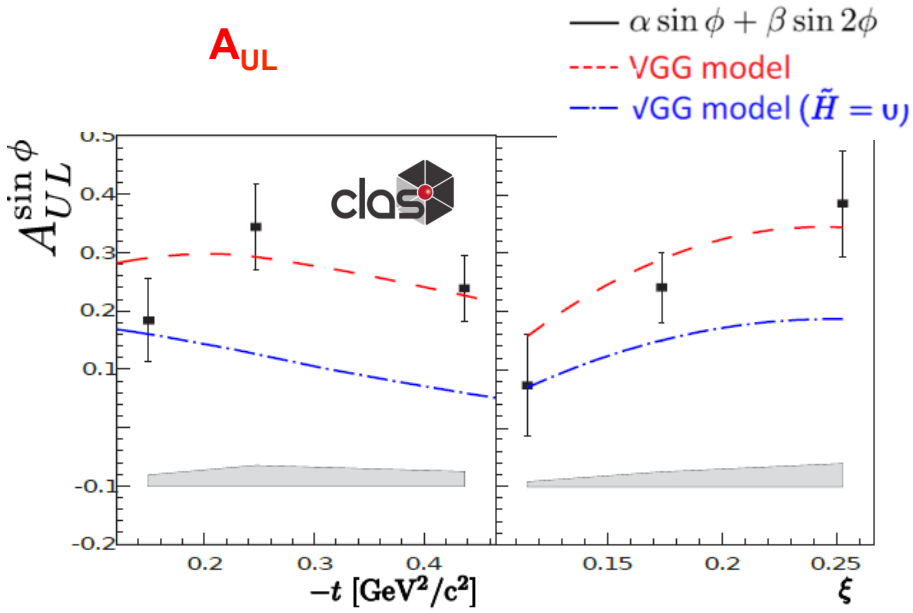
A_{LU}

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

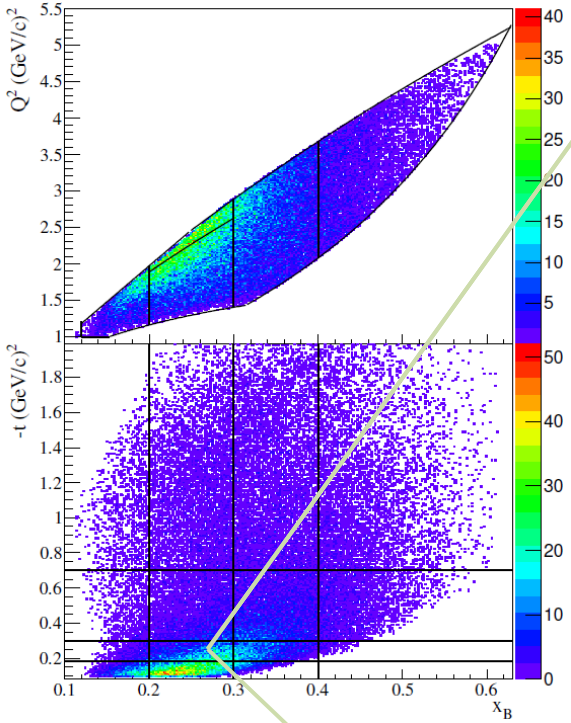


A_{UL}

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

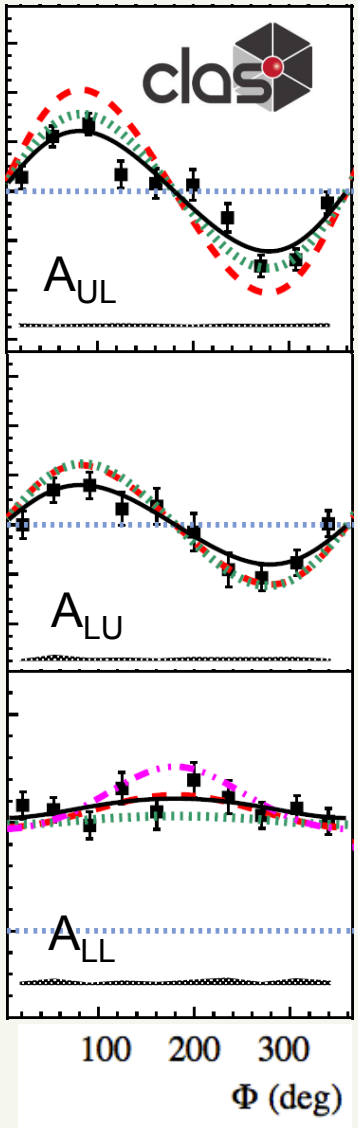


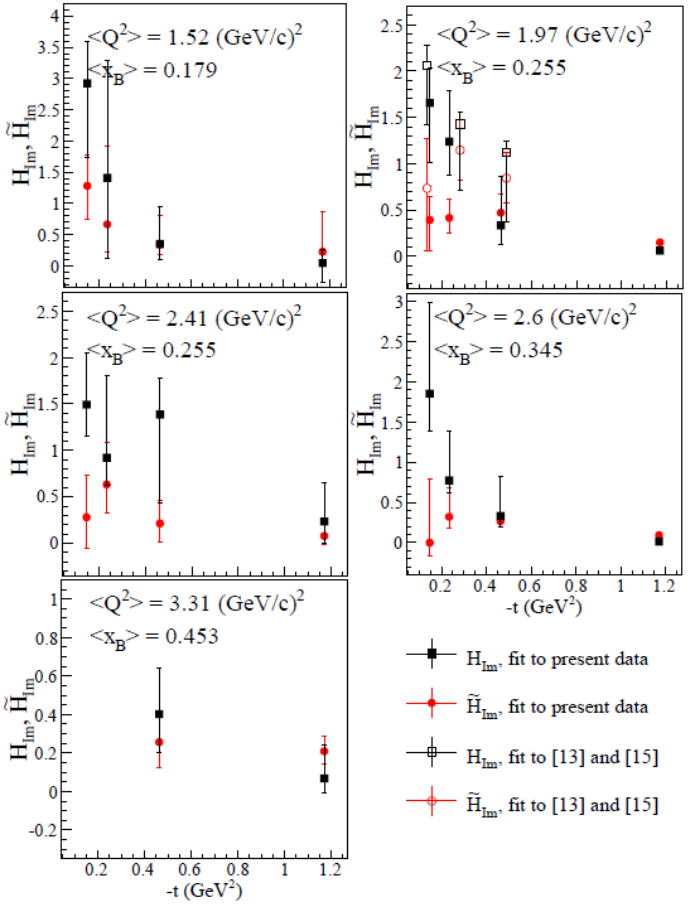
DVCS A_{LU}, A_{UL}, A_{LL} @ CLAS



High statistics extraction of Single and Double-spin asymmetries on NH_3

Simultaneous CFF extraction from three observables in a common kinematics





E. Seder et al, PRL114, 032001 (2015) [arXiv: 1410.6615]

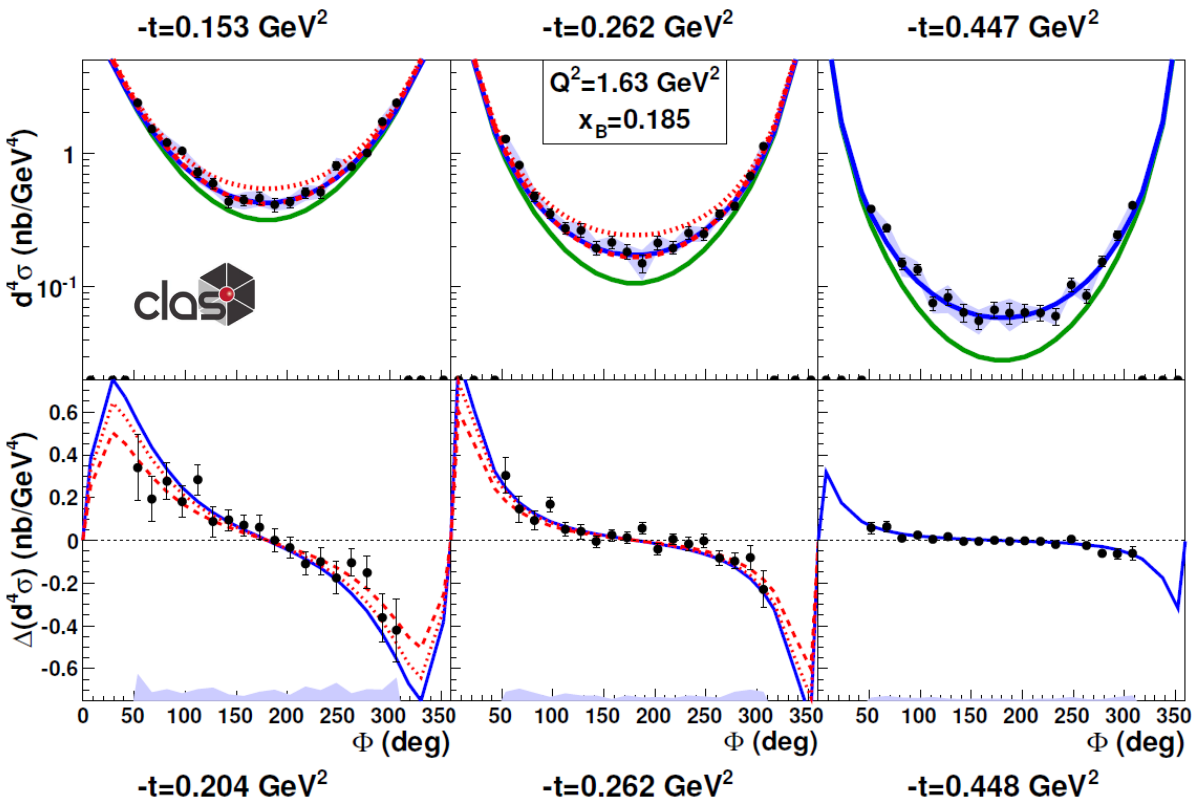
S. Pisano et al., PRD91, 5 052014 (2015) [arXiv: 1501.07052]

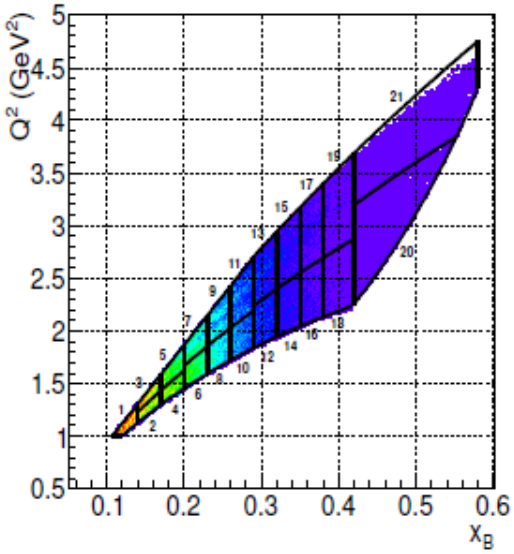
DVCS X-sec on Proton @ CLAS

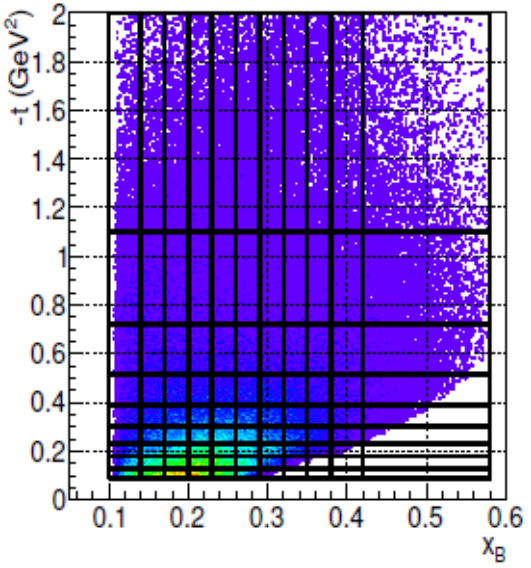
DVCS xsec on LH_2 in a large kinematics domain (110 bins)

$$\frac{d^4\sigma^{ep\to e'p\gamma}}{dx\ dQ^2 dt\ d\varphi}$$

BH only
VGG (H only)
KM10 (Kumericki, Mueller)
KM10a



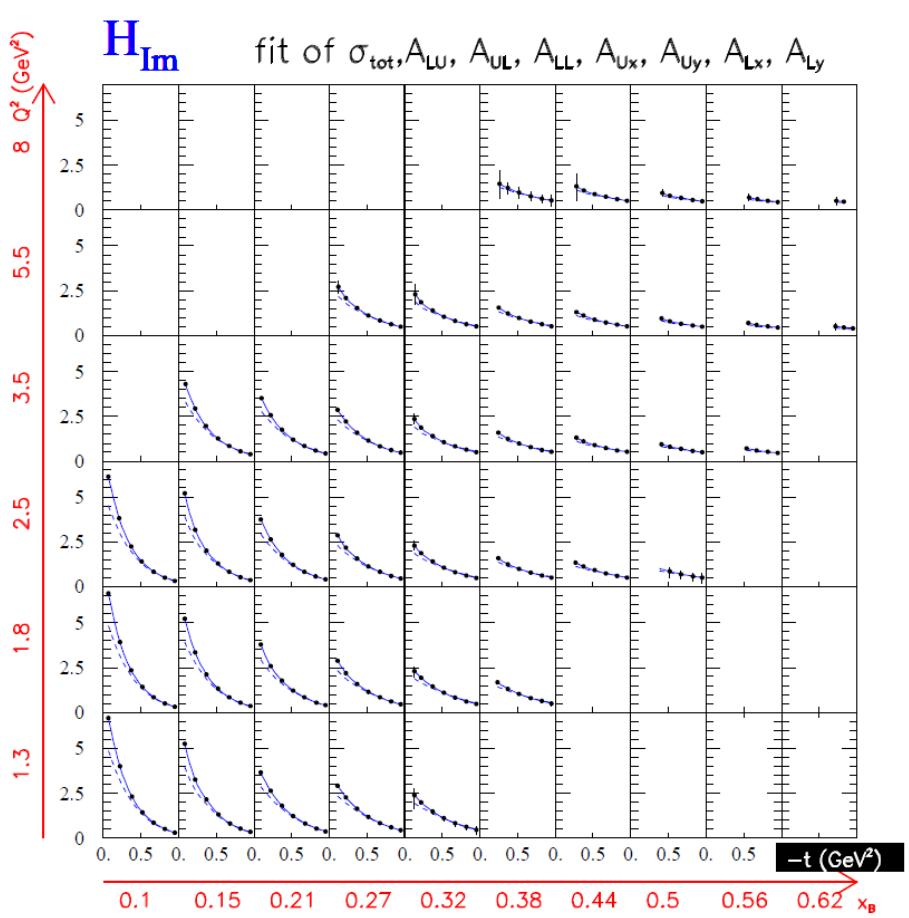


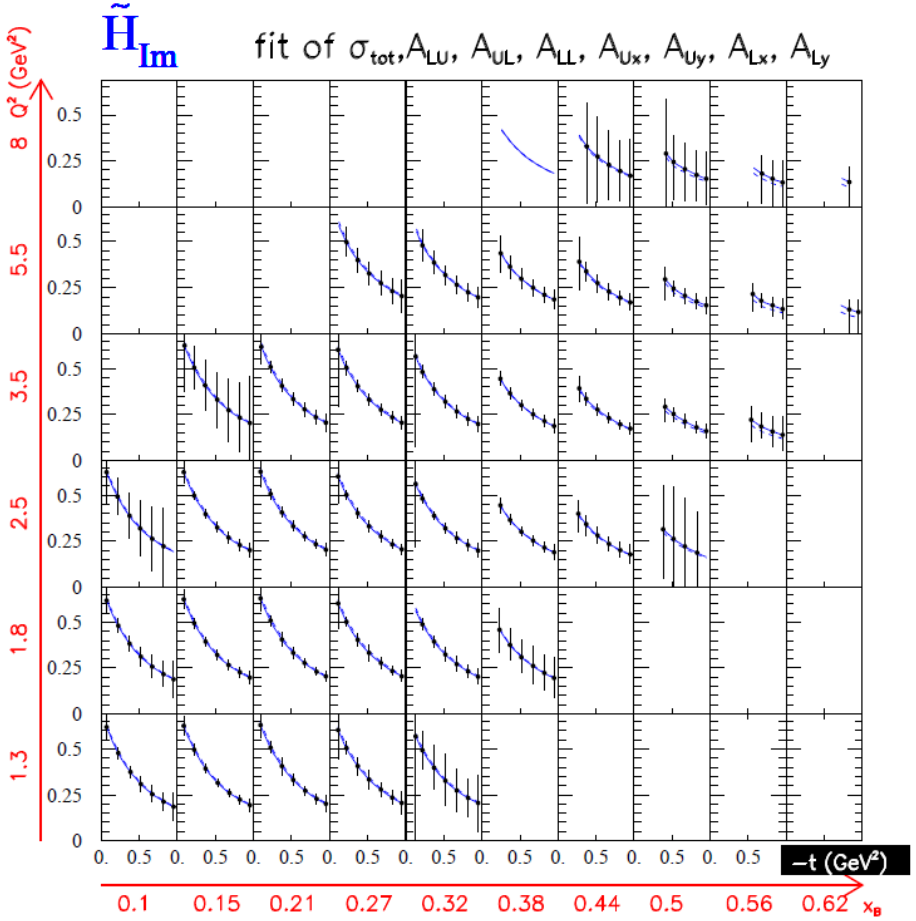


H. S. Jo et. al. [arXiv: 1504.02009]

Impact of CLAS12 Data

φ distribution in any (x, -t, Q^2) bin
CLAS acceptance & efficiencies included





M. Guidal, H. Moutarde, M. Vanderhaeghen [arXiv:1303.6600]

Quark Orbital Momentum @ CLAS12

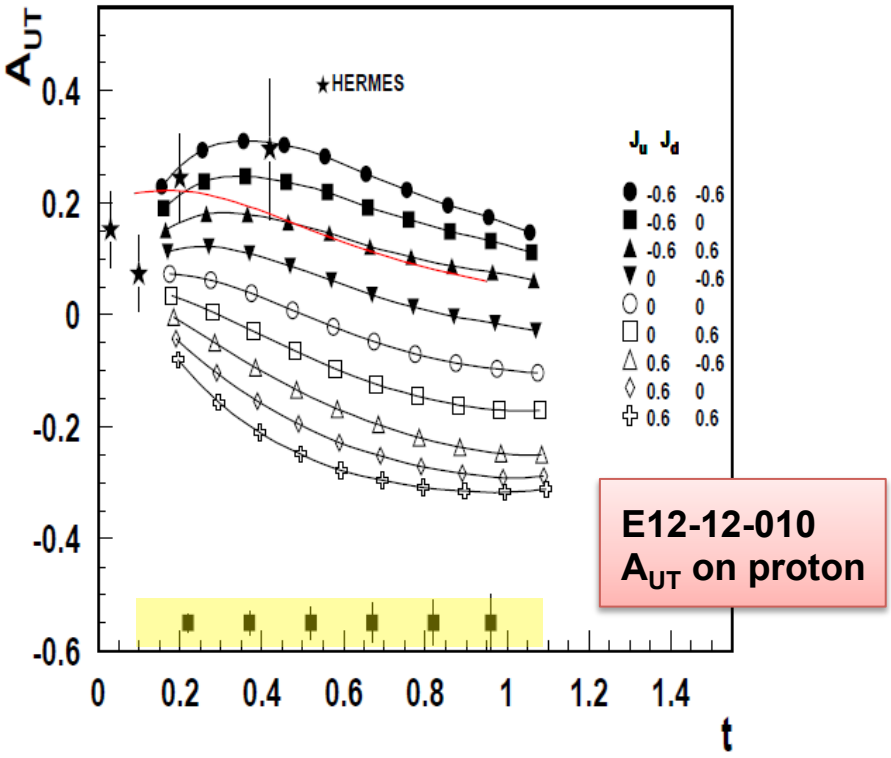
$$J_q = \frac{1}{2}\int_{-1}^{+1} dx\, x\, [H^q(x,\xi,t=0) + E^q(x,\xi,t=0)]$$

To access E_u & E_d both E_p & E_n are needed

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

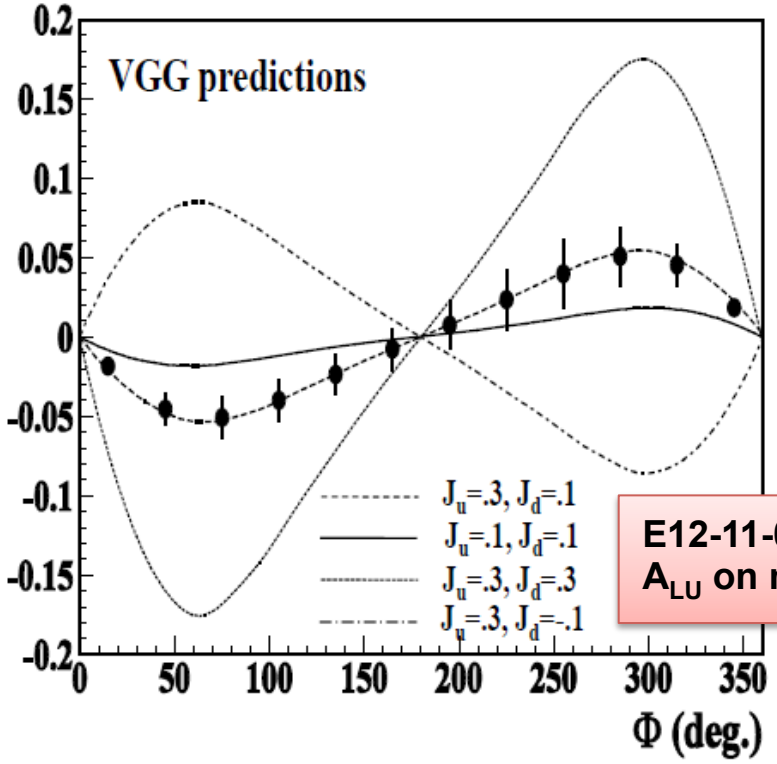
$(H,E)_d(\xi,\xi,t) = 9/15[\, 4(H,E)_n - (H,E)_p\,]$

Proton GPD



E12-12-010
A_{UT} on proton

Neutron GPD



E12-11-003
A_{LU} on neutron

Conclusions

CLAS @ HallB: a wide-acceptance high-luminosity high-polarization experiment for a comprehensive study of the partonic transverse degree of freedoms in the nucleon

Precise mapping of TMDs (pdf & FF) and GPDs in a multi-D approach

- Constrain models in the valence region
- Test factorization
- Study higher twist effects
- Investigate non-perturbative to perturbative transition (along P_T)
- Flavor separation via proton and deuteron targets and hadron ID
- Test of Lattice QCD calculations: tensor charge
- Access to OAM