11th Workshop on Hadron physics in China and Opportunities Worldwide

August 23 - 28, 2019

Nannkai University

3D nucleon structure programm in Hall B at JLab

Stefan Diehl

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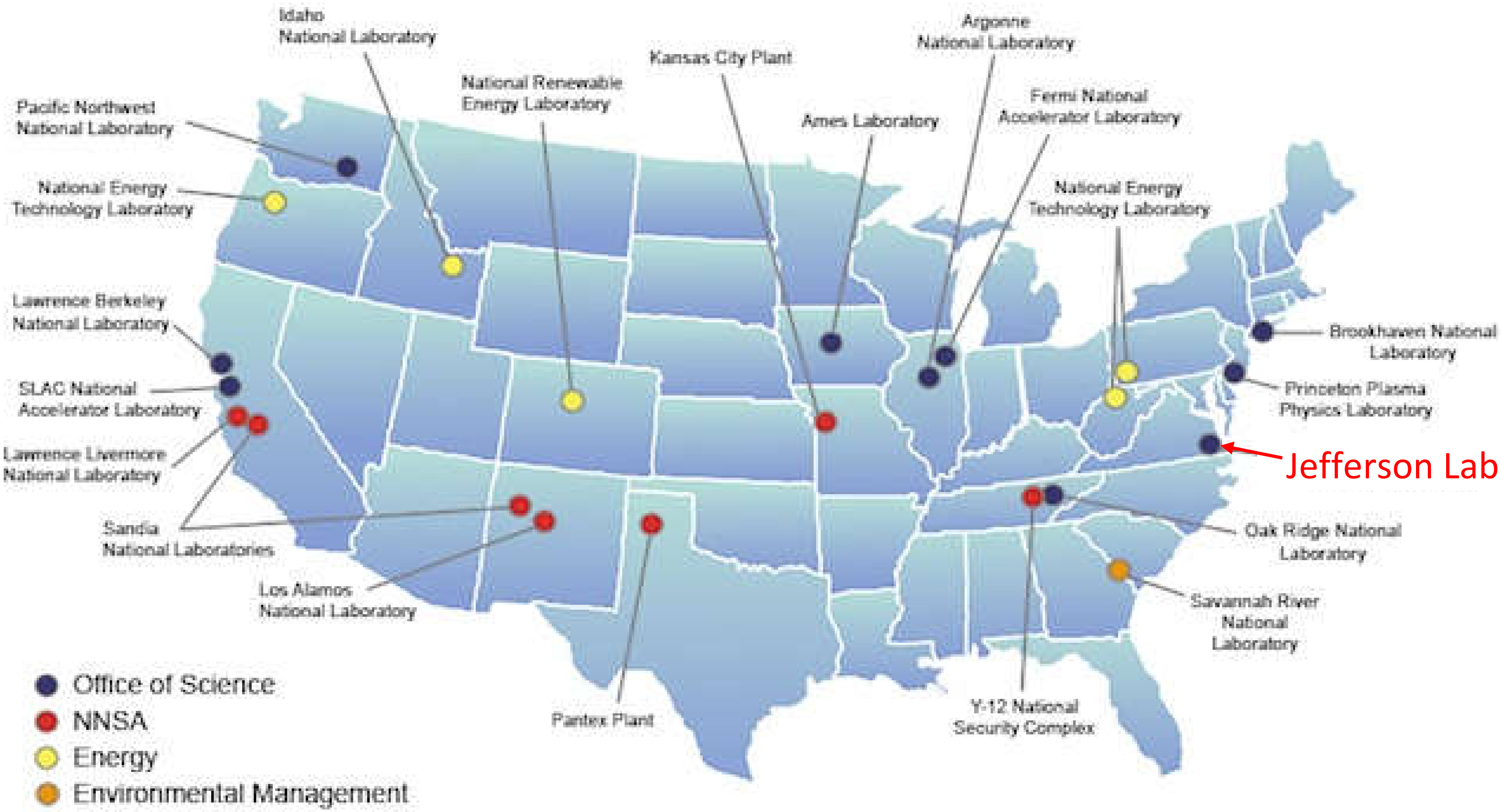
August 23, 2019

Thomas Jefferson National Accelerator Facility (Jefferson Lab)



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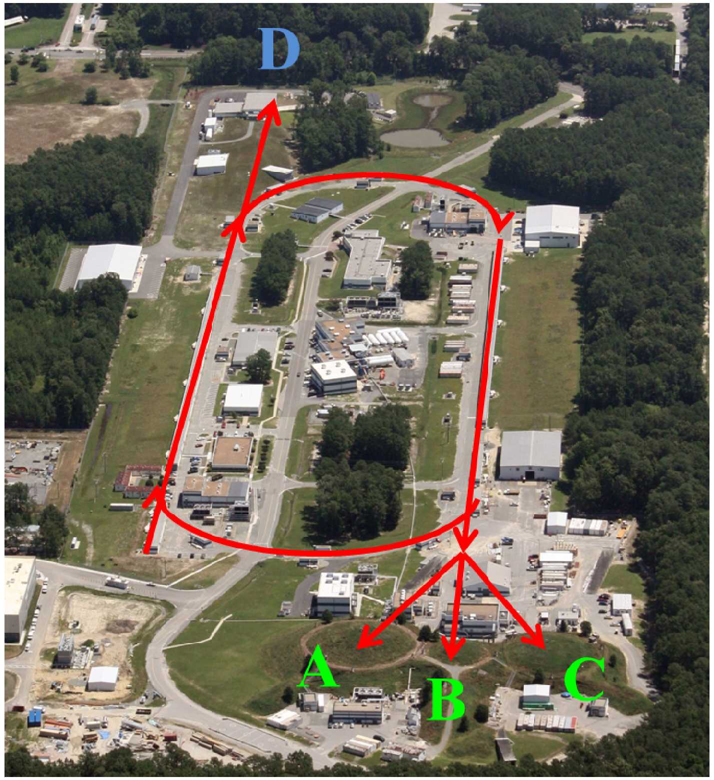
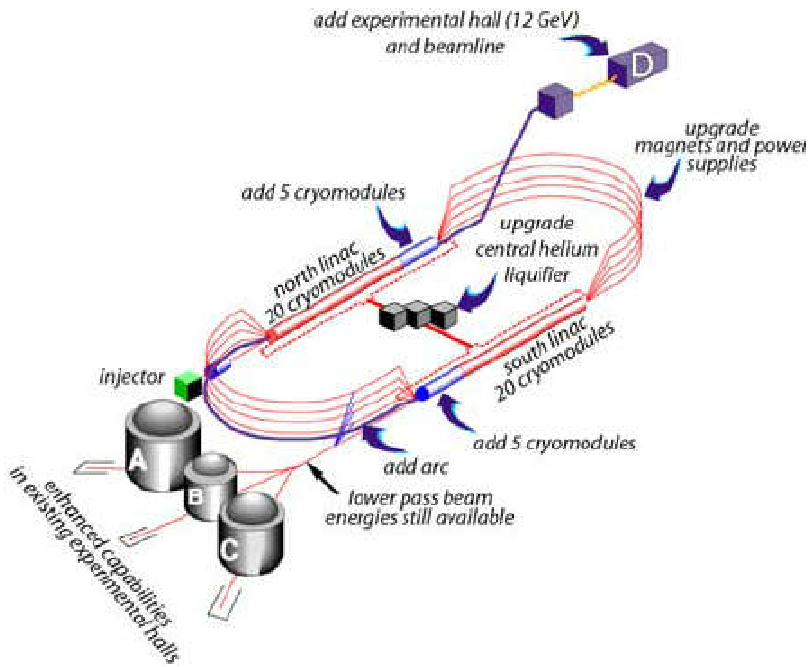


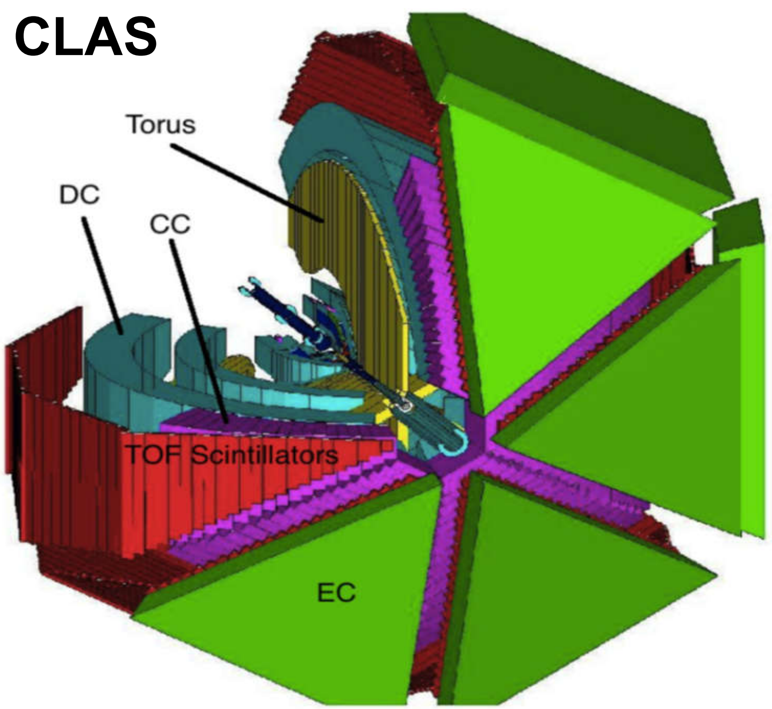


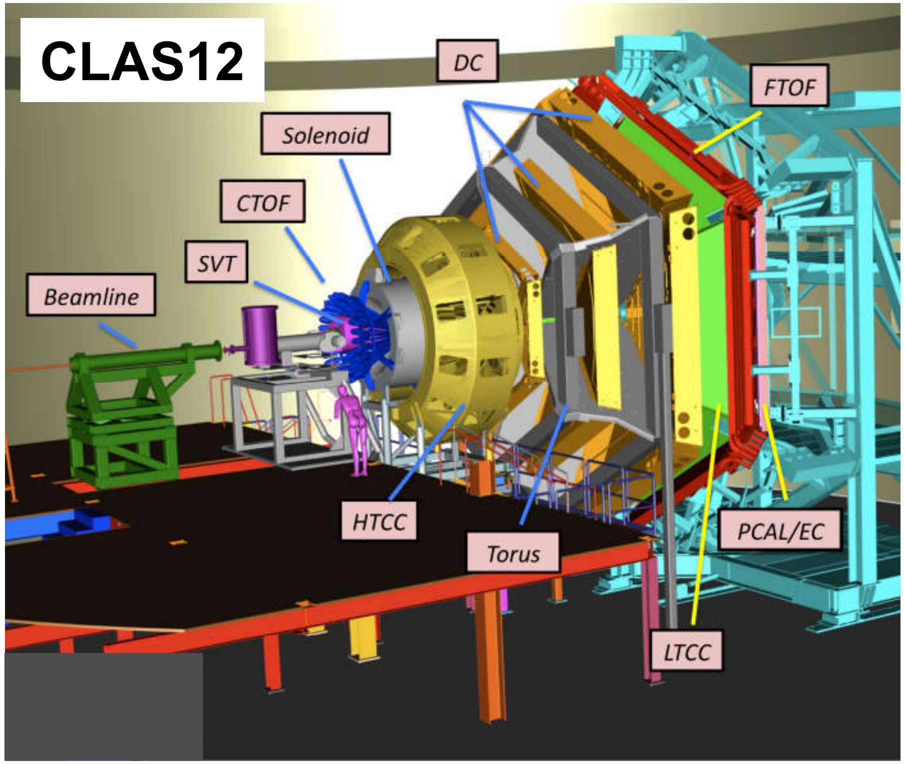
- CEBAF Upgrade completed in September 2017
  - → electron beam
  - → E_{max} = 12 GeV
  - → I_{max} = 90 μA
  - → Pol_{max} ~ 90%

Physics Operation

- 4 halls running simultaneously since January 2018
- Highest intensity tagged photon beam at 9 GeV
- World-record polarized electron beams
- Nuclear experiments at ultra-high luminosities, up to 10^{39} electrons-nucleons /cm^2/s

CLAS / CLAS12 in Hall B at Jefferson Lab

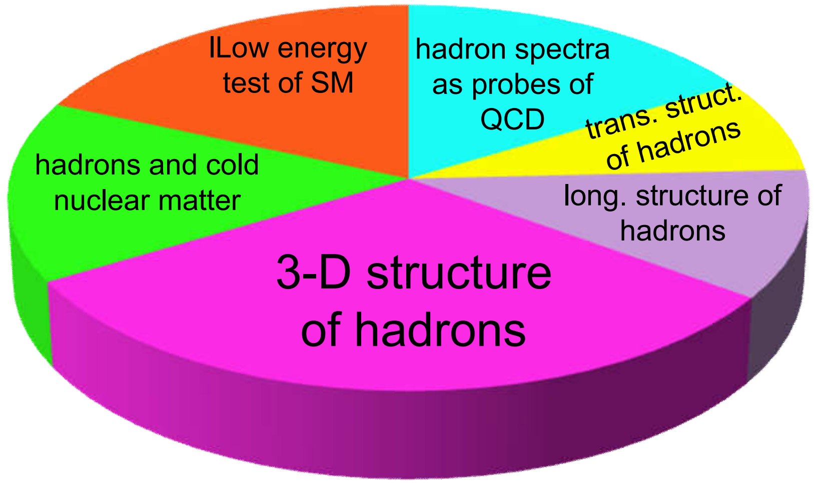




- $\mathcal{L} = 1 \times 10^{35}$ cm^{-2}s^{-1}
- Inclusive electron trigger (all calibration reactions will be analyzed in parallel)
- Electrons in the forward detector
- Protons in the central detector and forward detector
- Photons in the forward detector and forward tagger

Jefferson Lab Experiments for the next decade

- JLab's primary mission is to explore the fundamental nature of confined states of quarks and gluons, including the nucleons that comprise the mass of the visible universe.
  - How are quarks confined in nuclear matter?
  - What is the internal landscape of protons and neutrons?
  - How do the properties of protons and neutrons emerge from their constituent quarks and gluons?
  - How do the nuclear forces that lead to nuclei, arise from the basic interactions?
  - Can we discover evidence for Physics beyond the standard model?



12 GeV Physics Program: A Decade of Approved Experiments

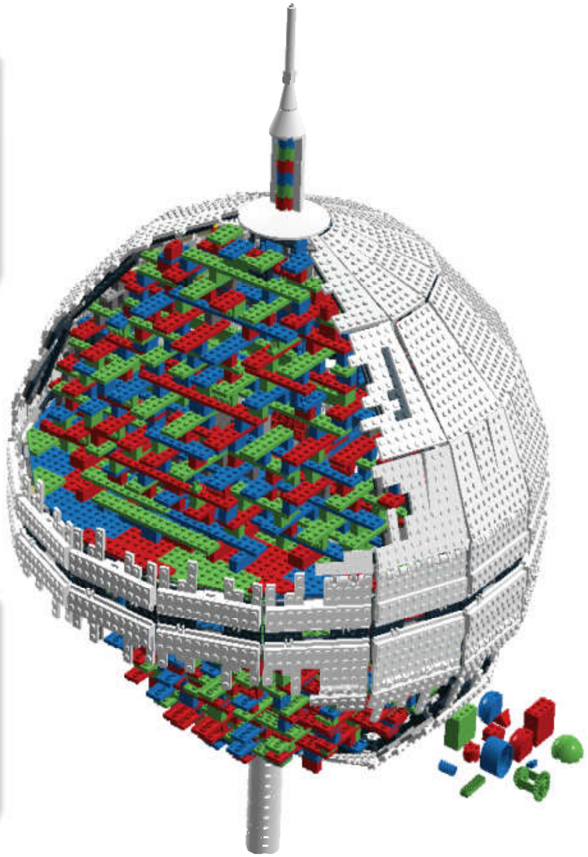
QCD Science Questions

How are the quarks and gluons, and their intrinsic spins distributed in space & momentum inside the nucleon?

How can we recover the well-known characterics of the nucleon from the properties of its **colored building blocks**?

Mass?
Spin?
Charge?
...

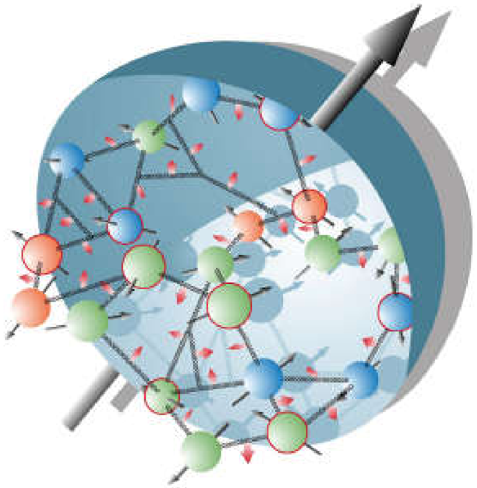
What are the relevant **effective degrees of freedom** and **effective interaction** at large distance?



What is the role of orbital angular motion?

The Incomplete Nucleon: Spin Puzzle

- Proton has spin-1/2
- Proton is a composite system consisting of spin-1/2 quarks and spin-1 gluons



This implies that the sum of angular momentum of quarks and gluons together must amount to 1/2. Can be due to:

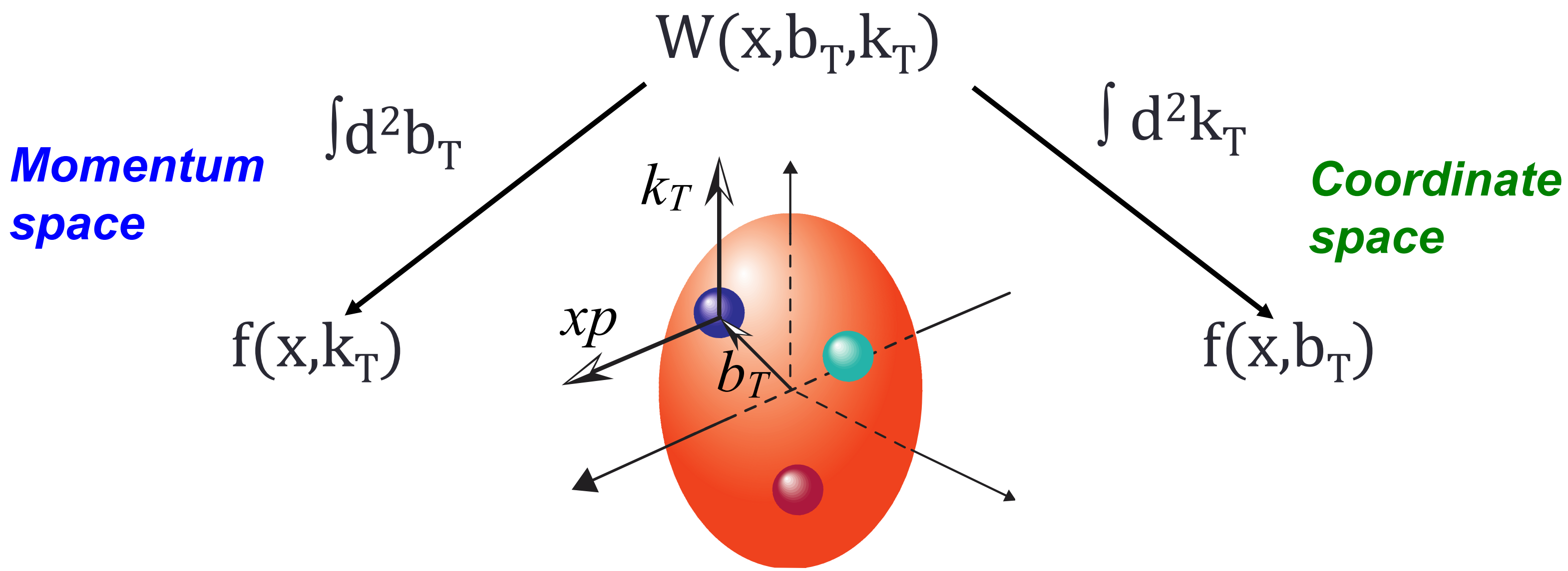
Quark spin	Quark orbital momentum
Gluon spin	Gluon orbital momentum

Classical: ~ **r** x **p**

Needs a cross-product or something three-dimensional!

3-Dimensional Imaging Quarks and Gluons

Wigner functions $W(x,b_T,k_T)$



Spin-dependent 3D momentum space images from semi-inclusive scattering
→ **TMDs**

Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering
→ **GPDs**

Position and momentum → Orbital motion of quarks and gluons

Generalized Parton Distributions (GPDs)

$$W_\Gamma(\mathbf{r},k) = \frac{1}{2M_N}\int \frac{d^3\mathbf{q}}{(2\pi)^3} e^{-i\mathbf{q}\cdot\mathbf{r}} \left\langle \mathbf{q}/2 \left| \hat{\mathcal{W}}_\Gamma(0,k) \right| -\mathbf{q}/2 \right\rangle ,$$

$$W_\Gamma(\mathbf{r},\mathbf{k}) = \int \frac{dk^-}{(2\pi)^2} W_\Gamma(\mathbf{r},k)$$

nucleon pol. / quark pol.

N/q	U	L	T
U	H		$\bar{E}_T$
L		$\widetilde{H}$	$\widetilde{E}_T$
T	E	$\widetilde{E}$	$H_T, \widetilde{H}_T$

$$\bar{E}_T = 2\widetilde{H}_T + E_T$$

Integrate over transverse ***momentum*** space

↓

Generalized Parton Distributions (GPD) H, $\tilde{H}$, E, $\tilde{E}$

↓

3-D nucleon imaging in transverse coordinate and longitudinal momentum space

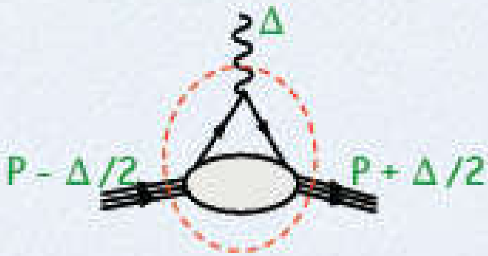
Interpretation of GPDs in the kinematic limits

- in forward kinematics (ξ=0, t = 0) : **PDF limit**

$$H^q(x, \xi = 0, t = 0) = q(x)$$
$$\tilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x)$$

$E, \tilde{E}^q$ do not appear in forward kinematics (DIS) ➡ **new information**

- first moments of GPDs : **elastic form factor limit**



t = Δ²

$$\int_{-1}^{+1} dx H^q(x, \xi, t) = F_1^q(t)$$ → Dirac FF

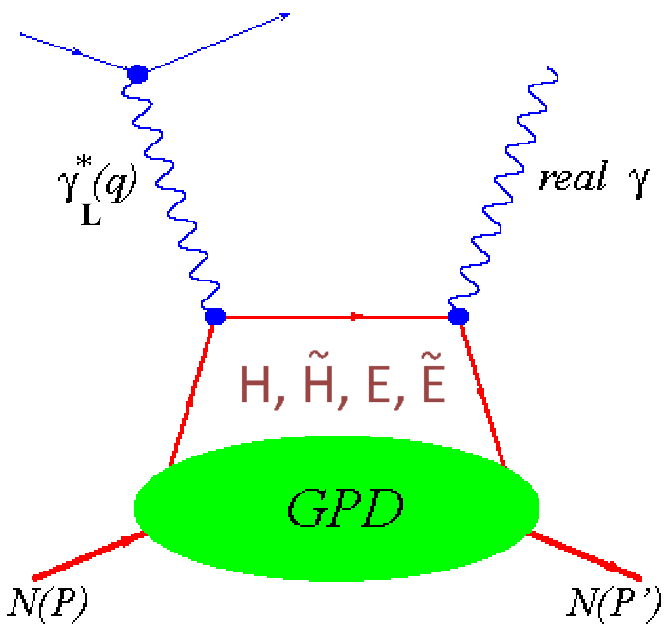
$$\int_{-1}^{+1} dx E^q(x, \xi, t) = F_2^q(t)$$ → Pauli FF

$$\int_{-1}^{+1} dx \tilde{H}^q(x, \xi, t) = G_A^q(t)$$ → axial FF

$$\int_{-1}^{+1} dx \tilde{E}^q(x, \xi, t) = G_P^q(t)$$ → pseudoscalar FF

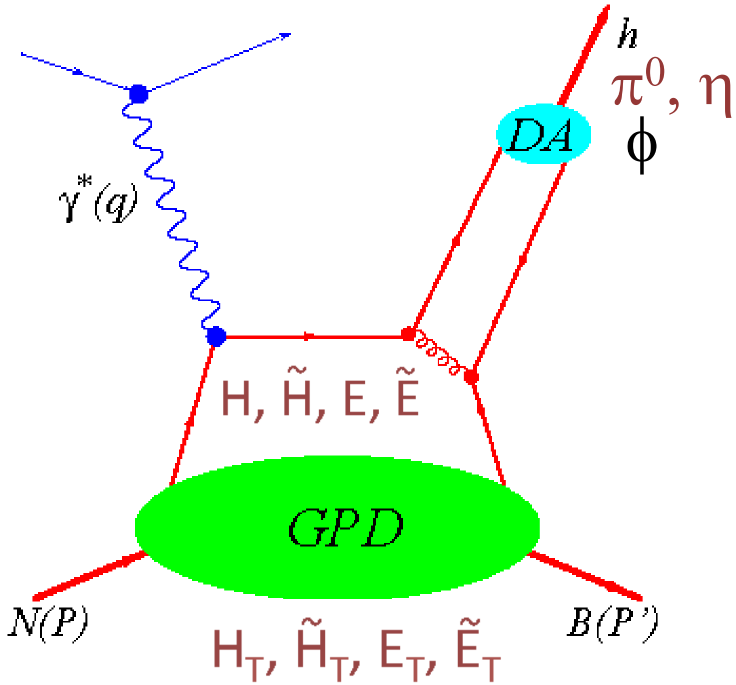
Study GPDs: Deeply Virtual Exclusive Processes

Deeply Virtual Compton Scattering (DVCS)



+ Clean process
- Only sensitive to chiral even GPDs

Deeply Virtual Meson Production (DVMP)

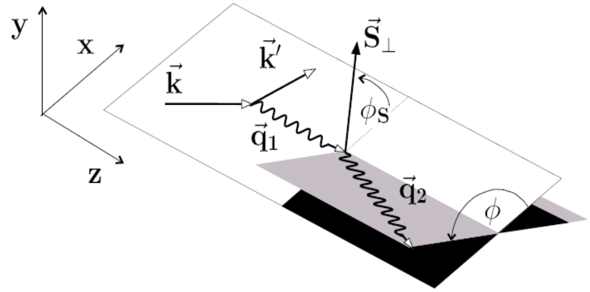


+ Enables Flavour decomposition of GPDs
+ Access to transversity degrees of freedom described by chiral-odd GPDs
- Distribution Amplitude (DA) is involved as additional soft non pert. Quantity

A path towards extracting GPDs

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

$$\xi \sim x_B/(2-x_B)$$
$$k = t/4M^2$$



Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi\ \{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi$$

→ $H(\xi,t)$

Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi\ \{F_1\tilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi)E)\}d\phi$$

→ $\tilde{H}(\xi,t)$

Unpolarized beam, transverse target:

$$\Delta\sigma_{UT} \sim \cos\phi\sin(\phi_s-\phi)\{k(F_2 H - F_1 E)\}d\phi$$

→ $E(\xi,t)$

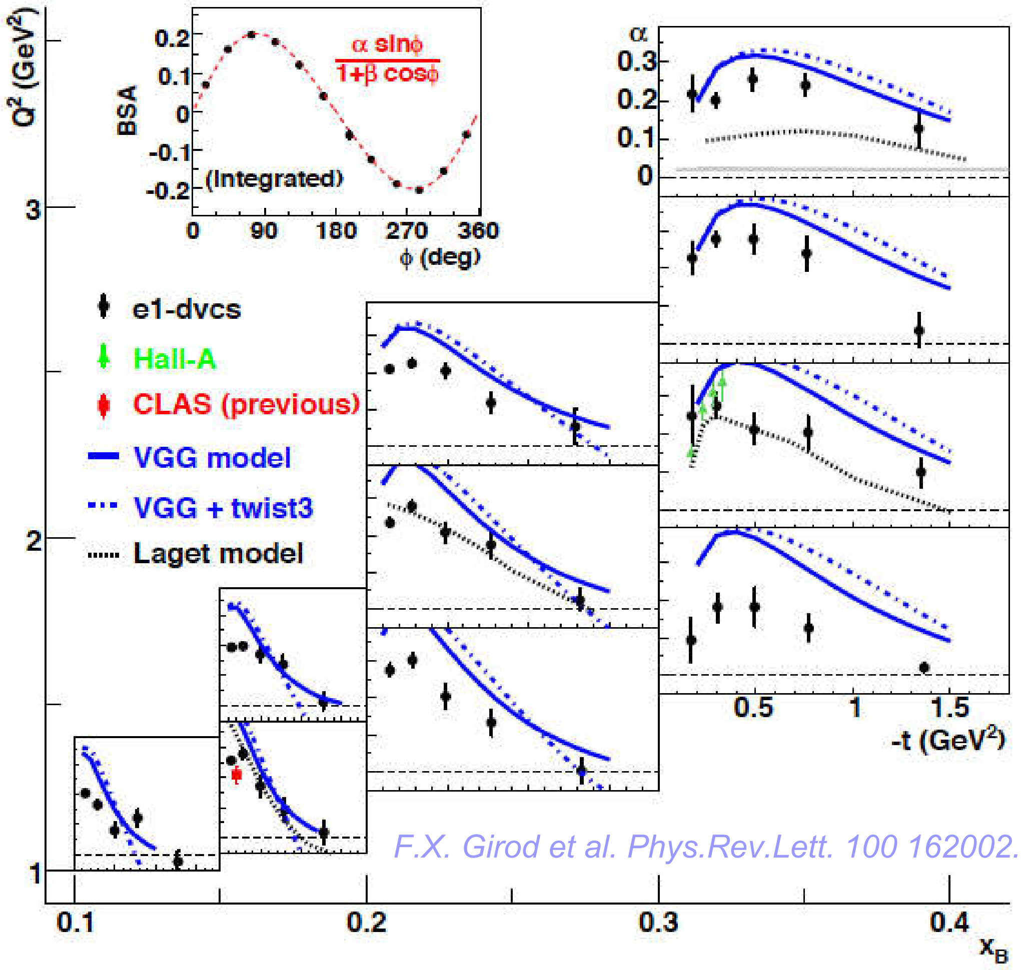
Unpolarized total cross section:

Separates h.t. contributions to DVCS

→ $\mathcal{R}e(T^{DVCS})$

DVCS Beam Spin Asymmetry

CLAS at 6 GeV

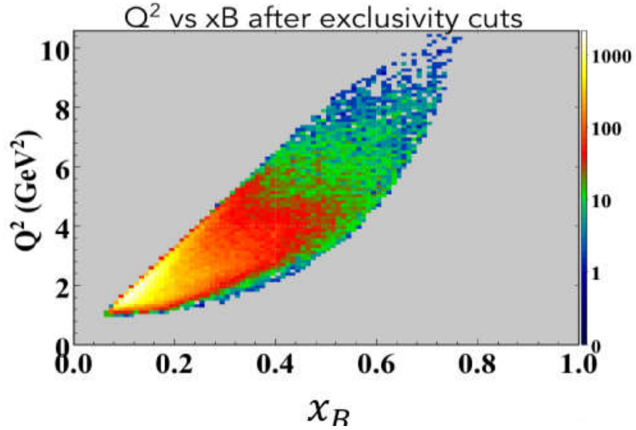


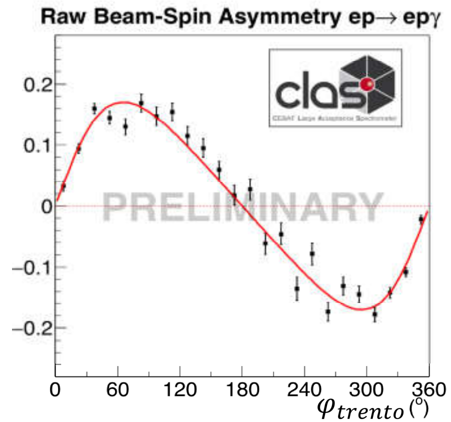
F.X. Girod et al. Phys.Rev.Lett. 100 162002.

Precision in a large phase space Q^2, x_B, t

CLAS12 at 10.6 GeV

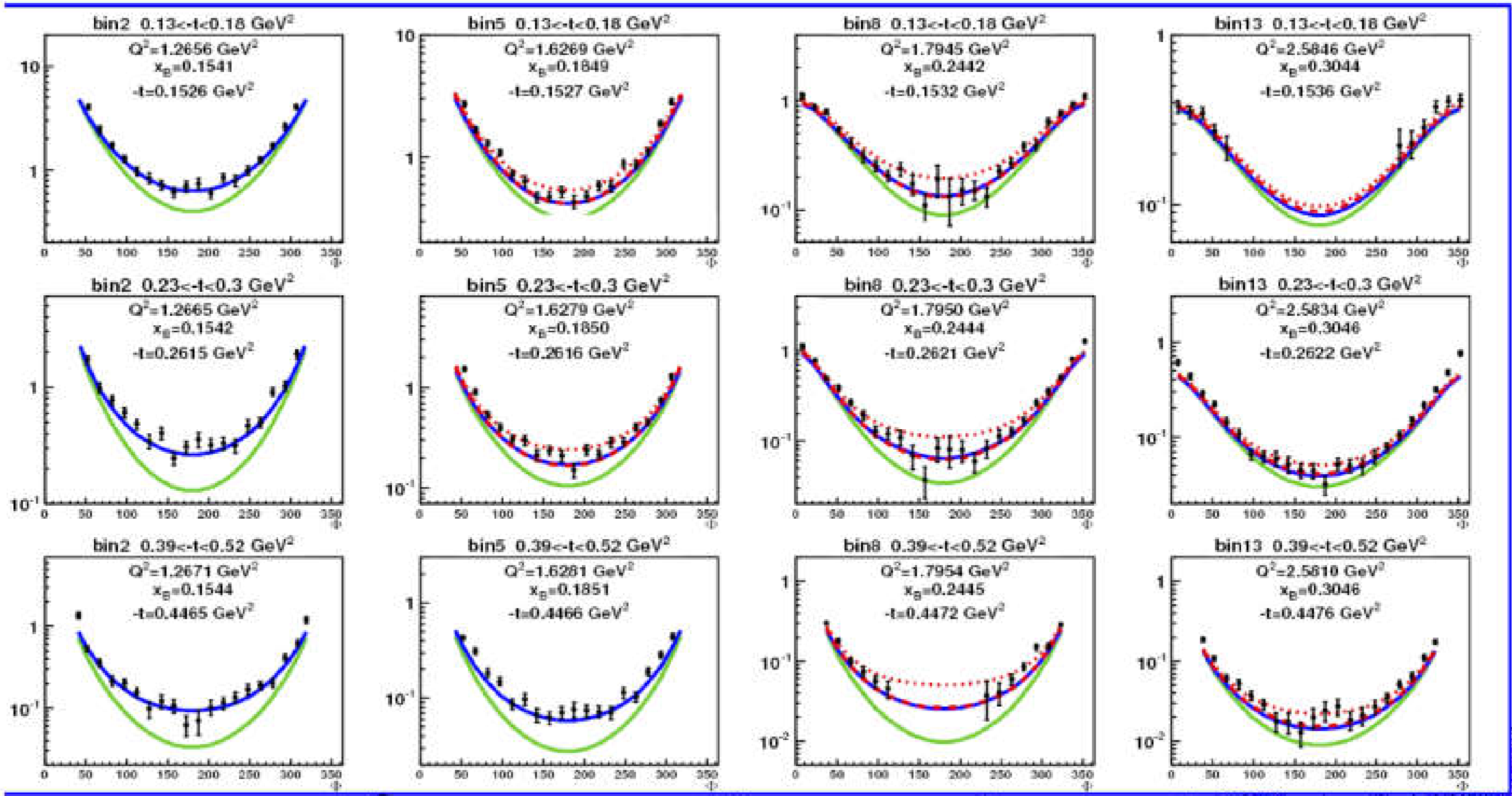
- extended kinematic coverage
- increased statistics
- neutron target





G. Christiaens

DVCS Unpolarized Cross-Sections with 6 GeV CLAS

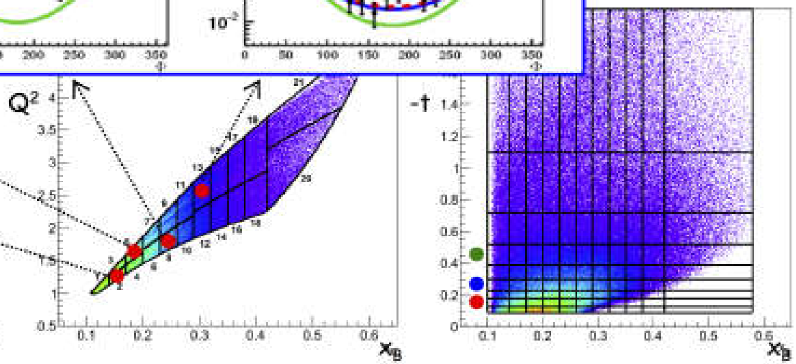


• $\frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi}$ (nb/GeV⁴)

—— BH —— VGG (H only)

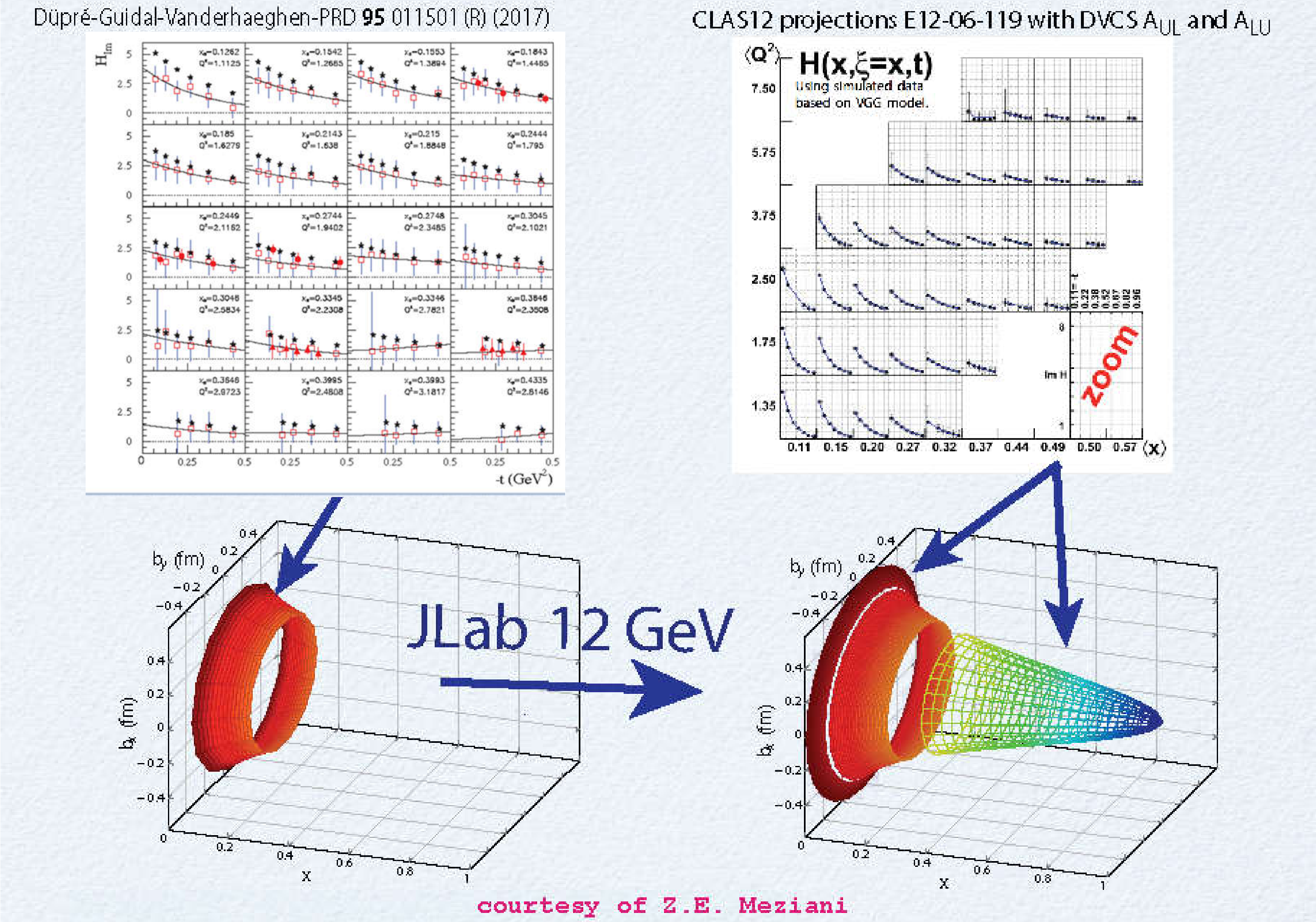
······ KM10 - - - KM10a

VGG : Vanderhaeghen, Guichon, Guidal *KM : Kumericki, Mueller*

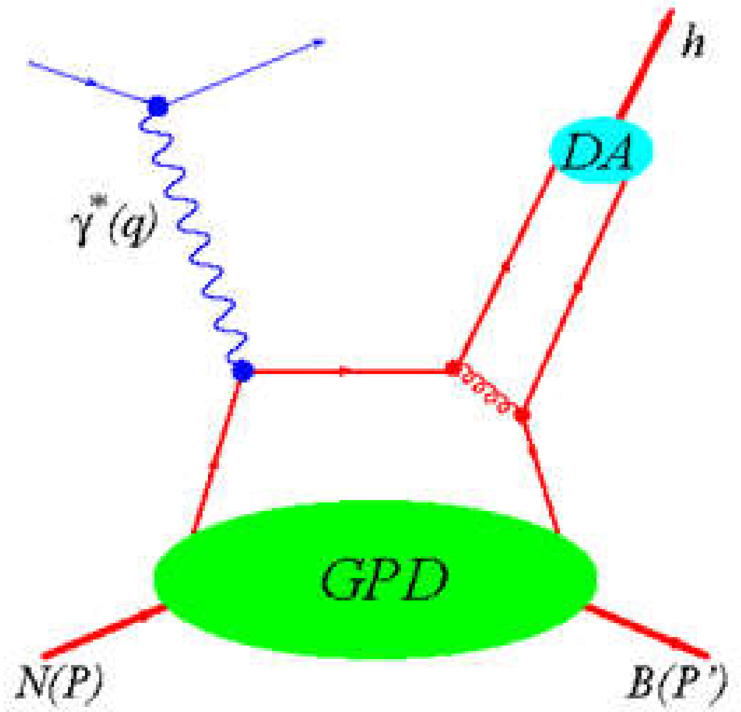


H.-S. Jo *et al.*, PRL 115 212003 (2015)

Projections for Compton Form Factors at JLab 12 GeV



Deeply Virtual Meson Production (DVMP)



	Meson	Flavor
$\mathcal{H}_T, \mathcal{E}_T$	π^+	$\Delta u - \Delta d$
	π^0	$2\Delta u + \Delta d$
	η	$2\Delta u - \Delta d + 2\Delta s$
$\mathcal{H}, \mathcal{E}$	ρ^+	$u - d$
	ρ^0	$2u + d$
	ω	$2u - d$
	ϕ	g

H^q	$\tilde{H}^q$	E^q	$\tilde{E}^q$	parton helicity conserving (chiral-even) GPDs
H_T^q	$\tilde{H}_T^q$	E_T^q	$\tilde{E}_T^q$	parton helicity-flip (chiral-odd) GPDs

Chiral-odd / transversity GPDs

- Jaffe and Ji have shown that the first Mellin moment of transversity PDF $h_1^q(x)$ gives us the tensor charge δq

$$\delta q = \int_{-1}^{1} h_1^q(x) dx = \int_0 {}_1 (h_1^q(x) - \bar{h}_1^q(x)) dx$$

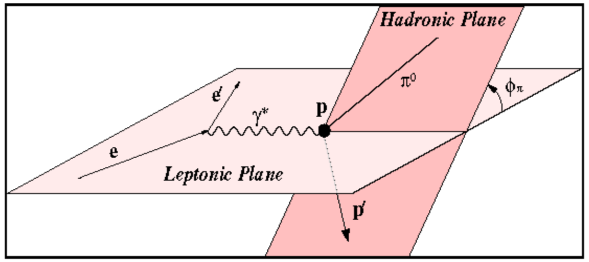
- We can interpret tensor charge as the absolute magnitude of transversely polarized valence quarks inside a transversely polarized nucleon.
- Given the relations between transversity PDF $h_1^q(x)$ and chiral-odd GPD $H_T(x, \xi, t)$ one can obtain the tensor charge δq through GPD in the forward limit:

$$h_1^q(x) = H_T(x, \xi = 0, t = 0)$$

Differential Cross Sections for hard exclusive meson production

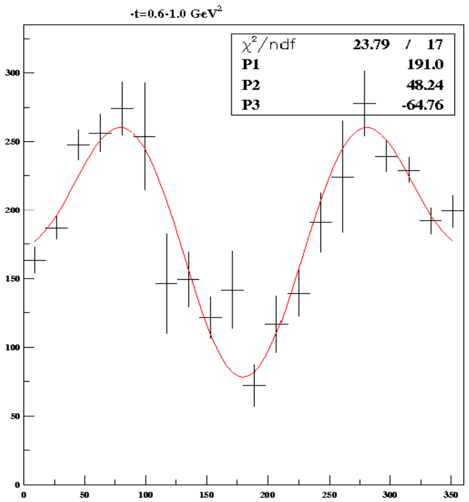
Structure Functions

$\sigma_U = \sigma_T + \varepsilon\sigma_L \quad \sigma_{TT} \quad \sigma_{LT}$

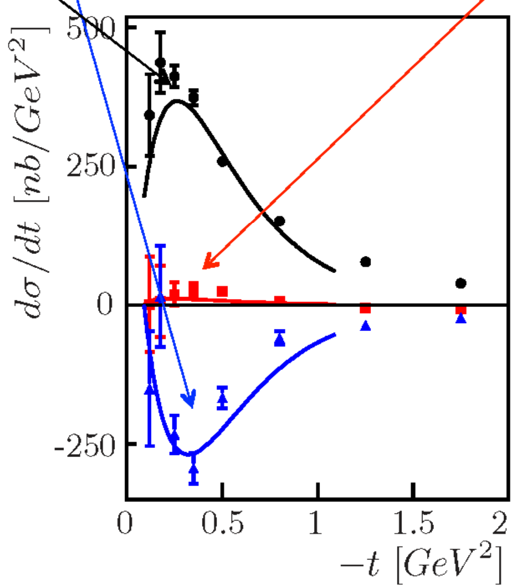


$ep \rightarrow ep\pi^0$

$$\frac{d\sigma}{dtd\phi}(Q^2,x,t,\phi) = \frac{1}{2\pi}\left(\frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt} + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi\right)$$



ϕ distribution



CLAS data and GPD theory predictions

2 theoretical models:

Golosokov, Kroll
Eur. Phys. J. A. 47: 112 (2011)

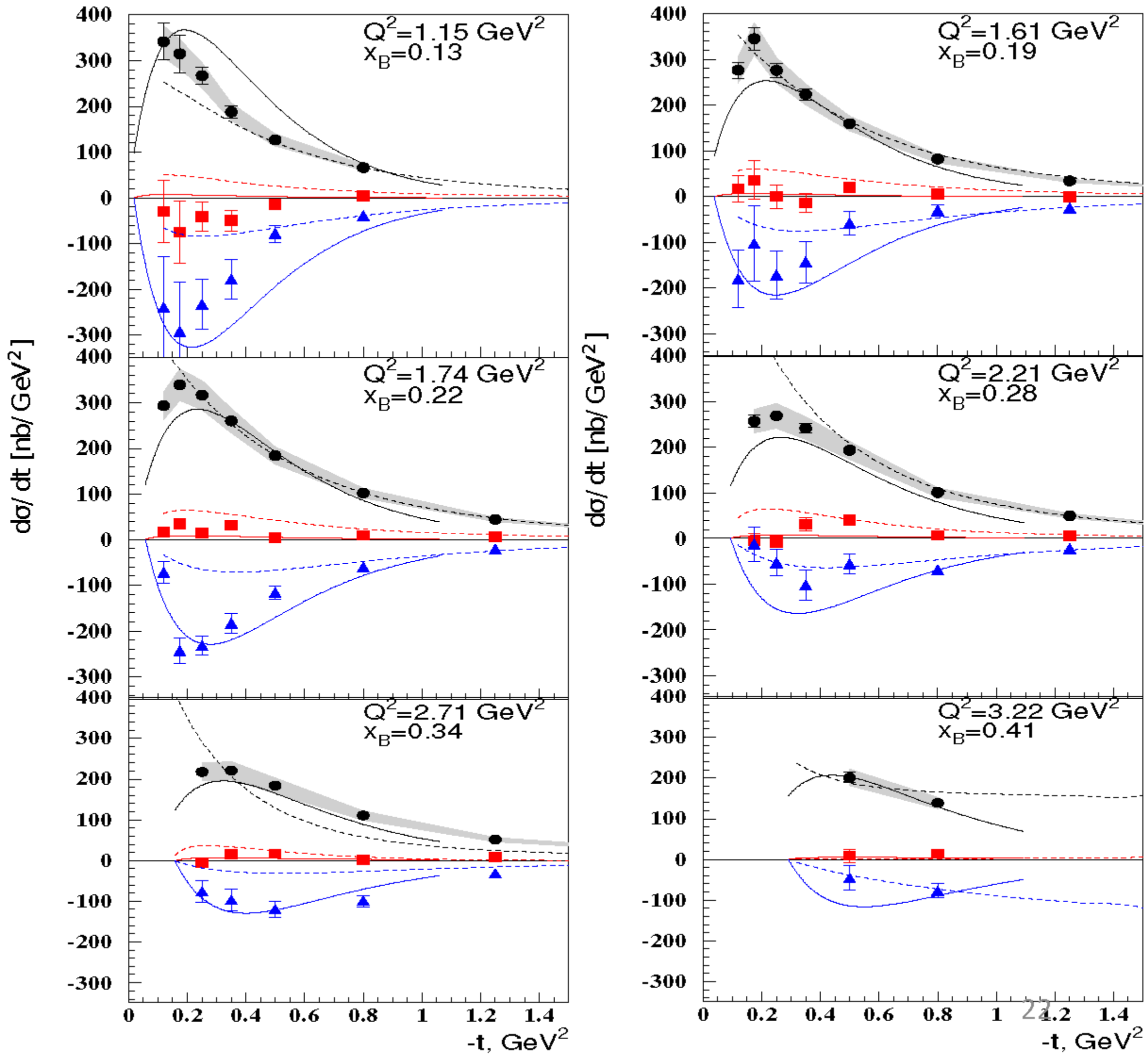
→ Only H_T and $\bar{E}_T$ have a significant contribution to pseudoscalar meson electroproduction

→ GPD parametrized based on data

Goldstein, Hernandez, Liuti
Phys. Rev. D 84, 034007 (2011)

→ Model allows flexible parametrization of GPDs

→ chiral-even and chiral-odd sector related with partiy relations of the helicity amplitudes



Solid: S. Goloskokov and P. Kroll
Dots: S. Liuti and G. Goldstein

CLAS collaboration. I Bedlinskiy et al. Phys.Rev.Lett. 109 (2012) 112001

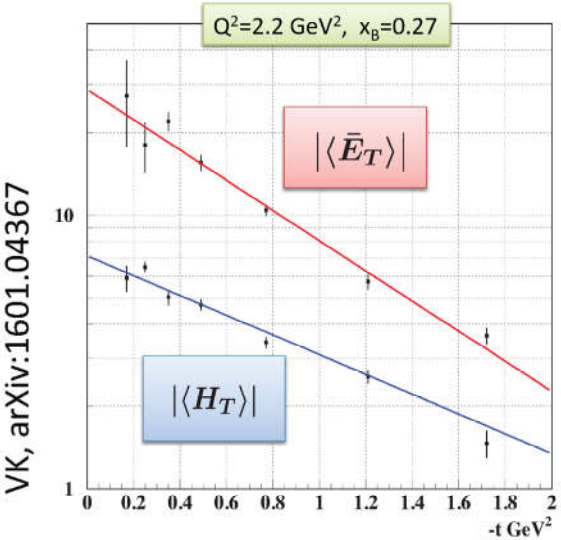
Extraction of form factors and flavour decomposition

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_P^2}{Q^8}\left[(1-\xi^2)\,|\langle H_T\rangle|^2 - \frac{t'}{8m^2}|\langle \bar{E}_T\rangle|^2\right]$$
$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_P^2}{Q^8}\frac{t'}{16m^2}|\langle \bar{E}_T\rangle|^2$$

Goloskokov, Kroll
Transversity GPD model

$$|\langle \bar{E}_T\rangle^{\pi,\eta}|^2 = \frac{k'}{4\pi\alpha}\frac{Q^8}{\mu_P^2}\frac{16m^2}{t'}\frac{d\sigma_{TT}^{\pi,\eta}}{dt}$$
$$|\langle H_T\rangle^{\pi,\eta}|^2 = \frac{2k'}{4\pi\alpha}\frac{Q^8}{\mu_P^2}\frac{1}{1-\xi^2}\left[\frac{d\sigma_T^{\pi,\eta}}{dt} + \frac{d\sigma_{TT}^{\pi,\eta}}{dt}\right]$$

π^0 Generalized Form Factors

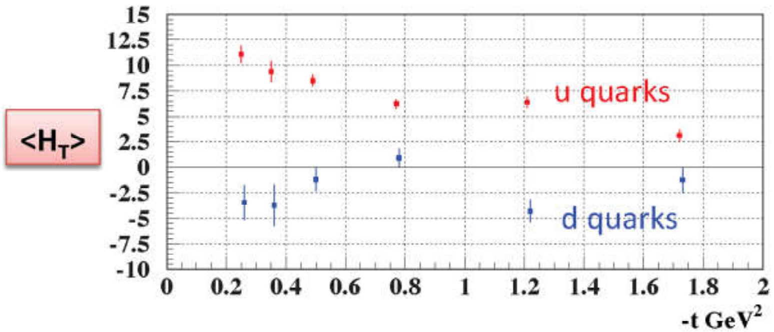


- E_T > H_T
- t-dependence is steeper for $\bar{E}_T$ than for H_T

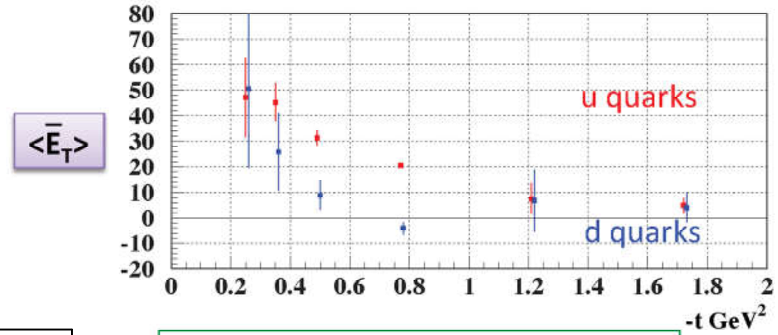
- GPDs appear in different flavor combinations for π^0 and η

$$H_T^{\pi} = \frac{1}{3\sqrt{2}}[2H_T^u + H_T^d]$$
$$H_T^{\eta} = \frac{1}{\sqrt{6}}[2H_T^u - H_T^d]$$

$$H_T^{u} = \frac{3}{2\sqrt{2}}[H_T^\pi + \sqrt{3}H_T^\eta]$$
$$H_T^{d} = \frac{3}{\sqrt{2}}[H_T^\pi - \sqrt{3}H_T^\eta]$$



- $\langle H_T\rangle^u$ and $\langle H_T\rangle^d$ have different signs for u and d- quarks



- $|\langle \bar{E}_T\rangle|^d$ and $|\langle \bar{E}_T\rangle|^u$ have the same signs

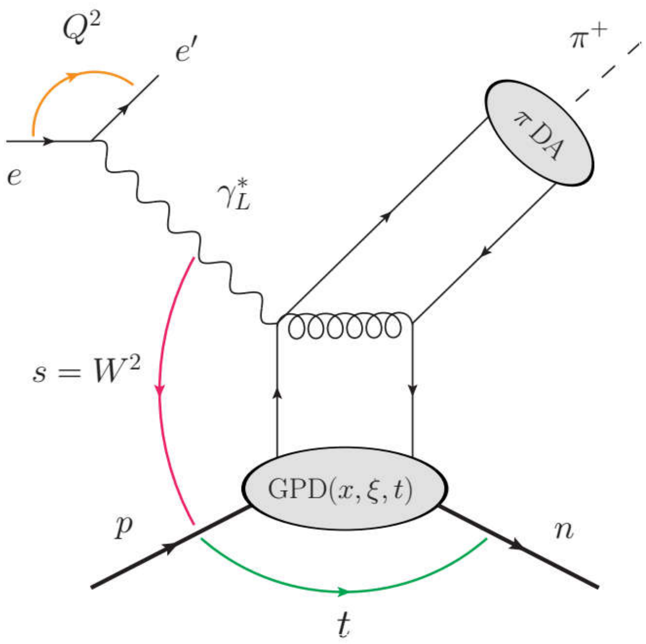
VK arXiv: 1601.04367 [hep-ex] 2016

GPD and TDA based descriptions

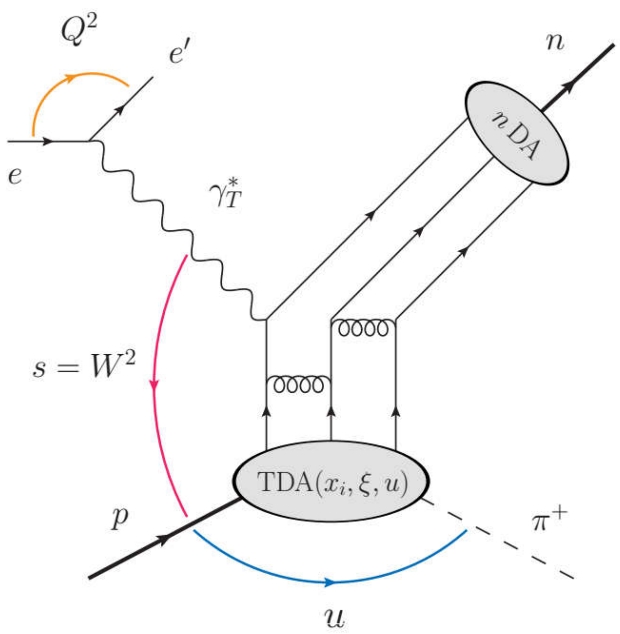
colinear factorization theorem

GPD based description
large Q^2 and s
small t channel contribution

TDA based description
large Q^2 and s
small u channel contribution



π in forward region



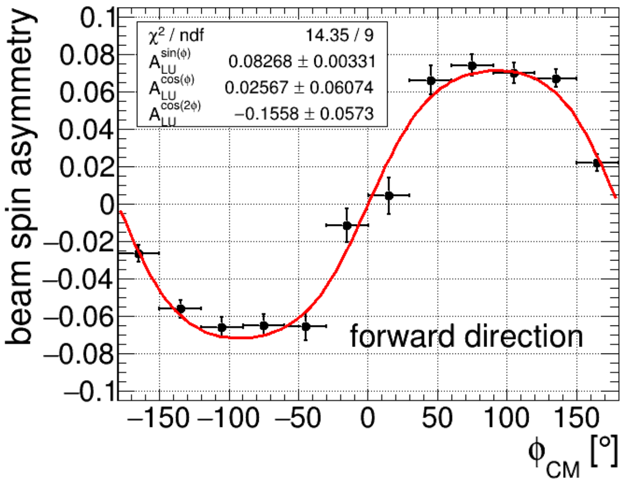
π in backward region

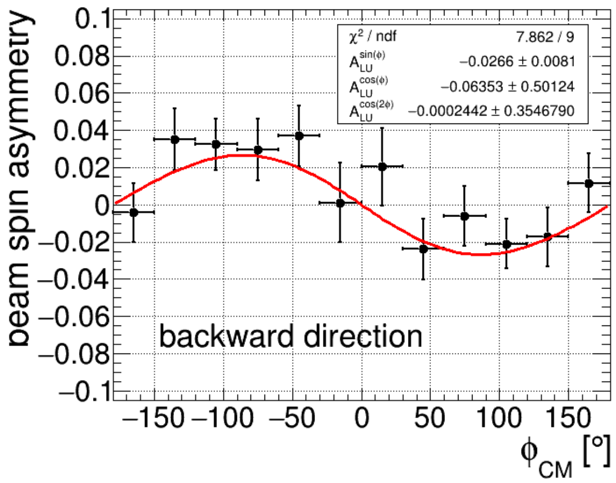
- ➔ probe partonic correlations between states of different baryonic charge
- ➔ access to non-minimal Fock components of baryon light-cone wave functions
- ➔ Femto-photography of hadrons from a new perspective
- ➔ Spatial imaging of the structure of the pion cloud inside the nucleon

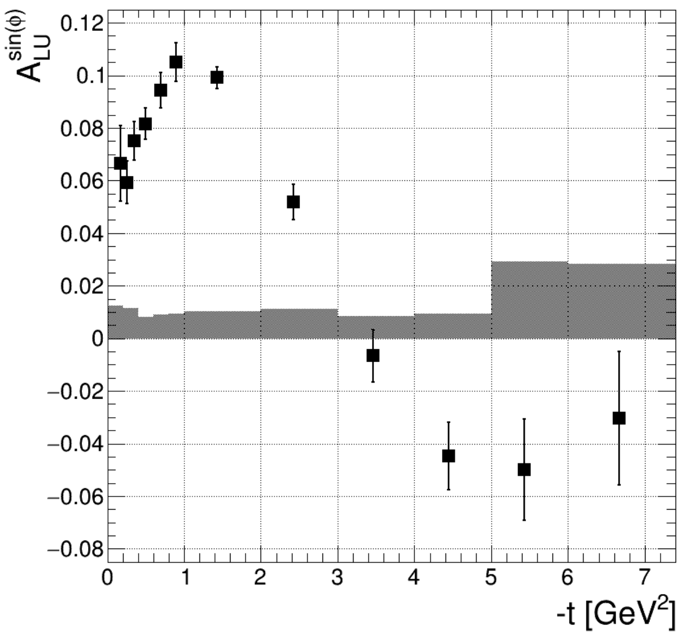
Extraction of $A_{LU}^{\sin(\phi)}$ for the hard exclusive π⁺ channel

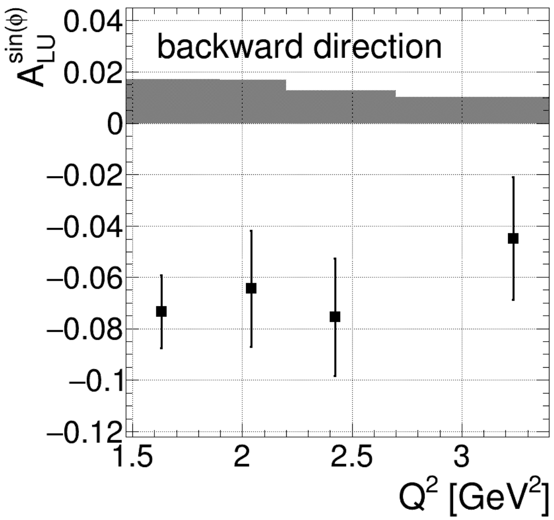
$$BSA_i = \frac{1}{P_e} \cdot \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

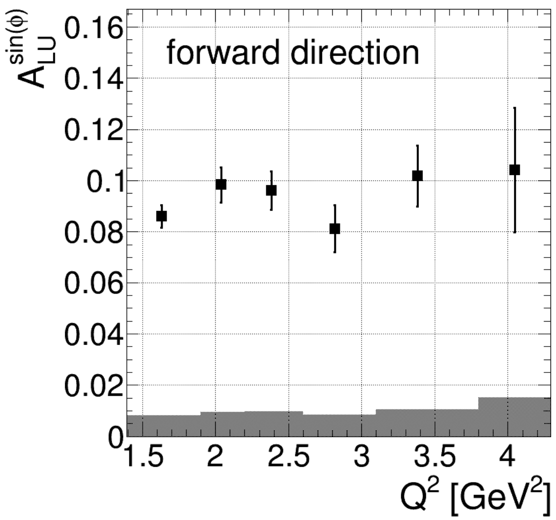
$$BSA = \frac{A_{LU}^{\sin\phi} \sin\phi}{1 + A_{UU}^{\cos\phi} \cos\phi + A_{UU}^{\cos(2\phi)} \cos(2\phi)}$$







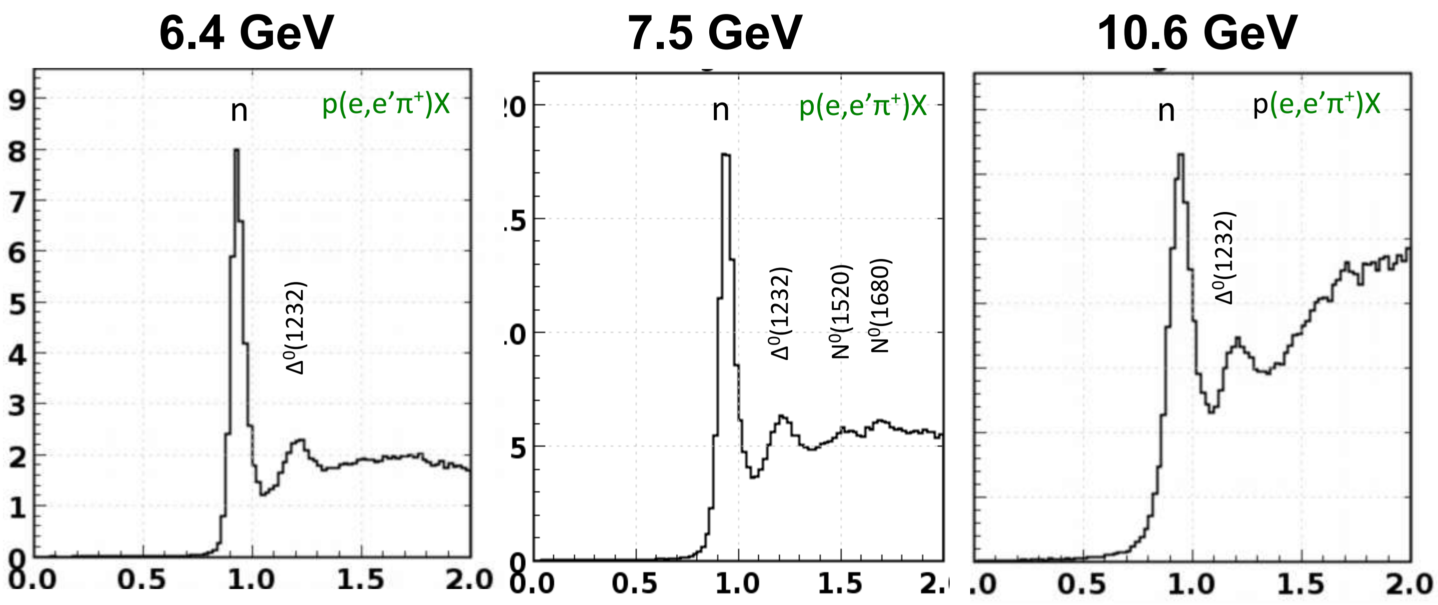




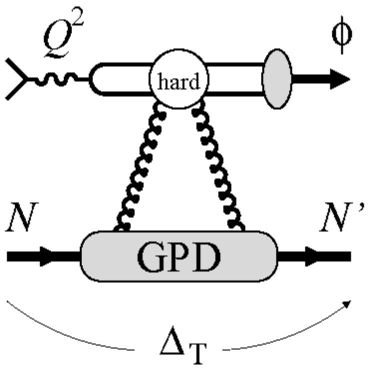
S. Diehl (JLU + UConn)

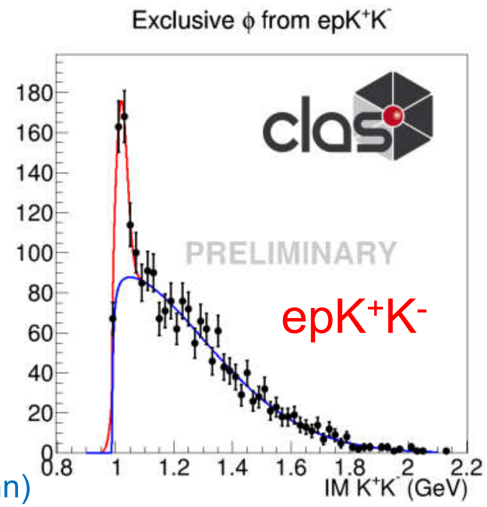
CLAS12 DVMP program just started ….

$$ep \to e\pi^+ X$$



Exclusive Φ Production





B. Clary (Uconn)

- Exclusive Φ production probes gluon GPDs
- Transverse spatial distribution of gluons

  x < 0.01 measured at HERA, FNAL

  x > 0.1 practically unknown

Transverse Momentum Distributions (TMDs)

- Spin-dependent 3D momentum space images from semi-inclusive scattering

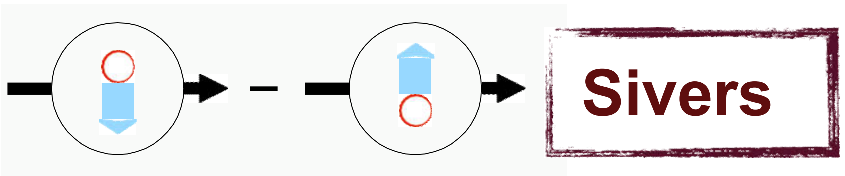
quark pol.

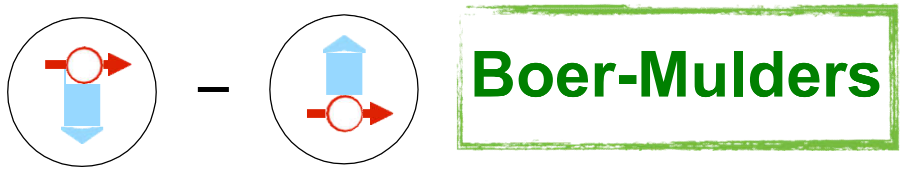
nucleon pol.	U	L	T
U	f_1		$h^{\perp}_1$
L		g_1	$h^{\perp}_{1L}$
T	$f^{\perp}_{T}$	g_{1T}	h_1, $h^{\perp}_{1T}$

- TMDs in black survive transverse - momentum integration
- TMDs in red are T - odd
- All colored TMDs vanish if there is no quark orbital angular momentum
- Any quantitative statement about the total orbital angular momentum is model dependent

Azimuthal asymmetries generated by correlations between quark transverse momentum and

the nucleon transverse spin   the parton transverse spin

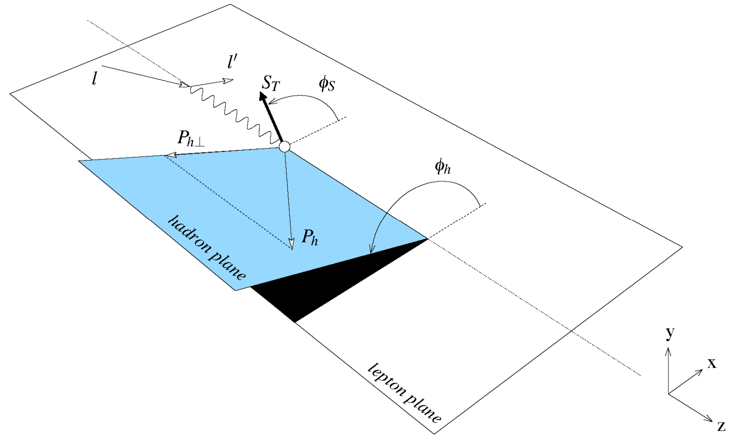




Semi-Inclusive Deep Inelastic Scattering (SIDIS)

$F_{UU,T}(x, z, P_{h\perp}^2, Q^2)$

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} &= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Big\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
&+ \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big] \\
&+ S_L\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big] \\
&+ S_T\Big[\sin(\phi_h-\phi_S)\,\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&+ \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&+ \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&+ \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}
\end{aligned}
$$



➔ **18 Structure Functions**

EXPERIMENT: Setting the proper beam and target polarization conditions (U, L, T)

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\Big[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\Big(xh\,H_1^\perp + \frac{M_h}{M}\,f_1\frac{\tilde{D}^\perp}{z}\Big) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\Big(xf^\perp D_1 + \frac{M_h}{M}\,h_1^\perp\frac{\tilde{H}}{z}\Big)\Big],$$

$$F_{UU}^{\cos 2\phi_h} = \mathcal{C}\Big[-\frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h}\,h_1^\perp H_1^\perp\Big],$$

$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = \mathcal{C}\Big[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\,f_{1T}^\perp D_1\Big]$$

Collins FF

Boer-Mulders

Sivers

Longitudinally polarized beam and unpolatized target

$$\frac{d\sigma}{dx_B\, dQ^2\, dz\, d\phi_h\, dp_{h\perp}^2} = K(x,y,Q^2)\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}\Big\}$$

$$F_{LU}^{\sin\phi} = \frac{2M}{Q}\mathcal{C}\left(-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M_h}\left(xeH_1^\perp + \frac{M_h}{M} f_1 \frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p_T}}{M}\left(xg^\perp D_1 + \frac{M_h}{M} h_1^\perp \frac{\tilde{E}}{z}\right)\right)$$

twist-3 pdf

Collins FF

unpolarized dist. function

twist-3 FF

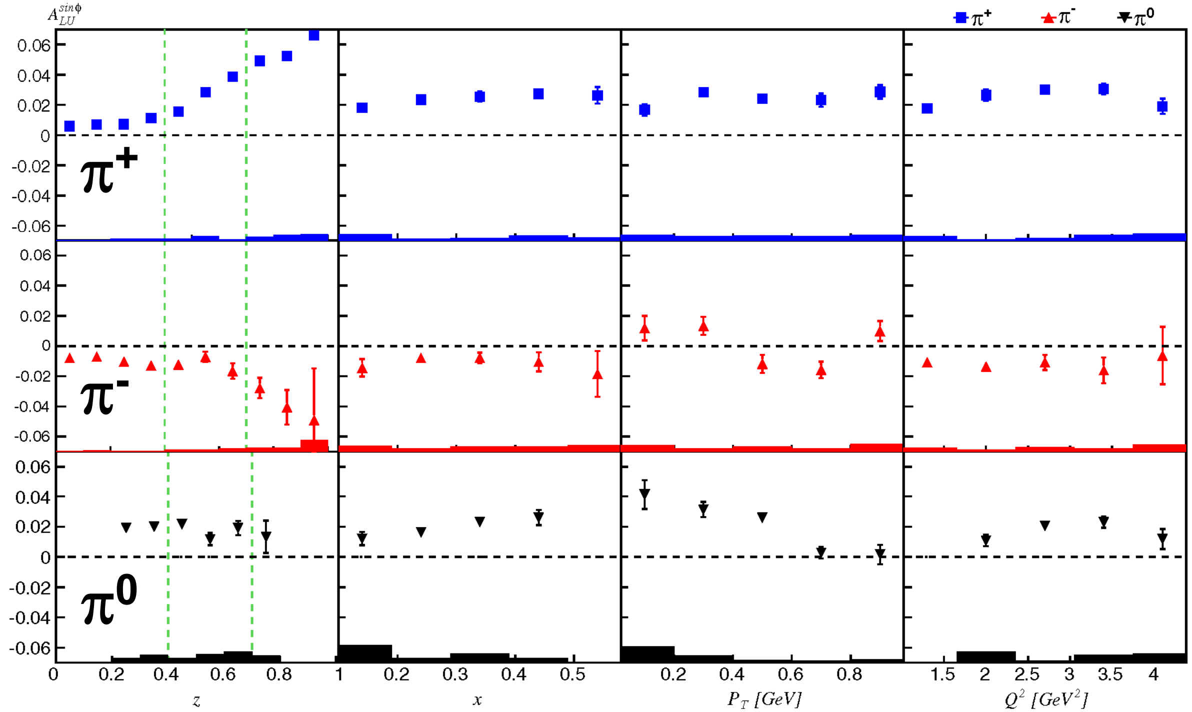
twist-3 t-odd dist. funcion

Boer-Mulders

twist-3 FF

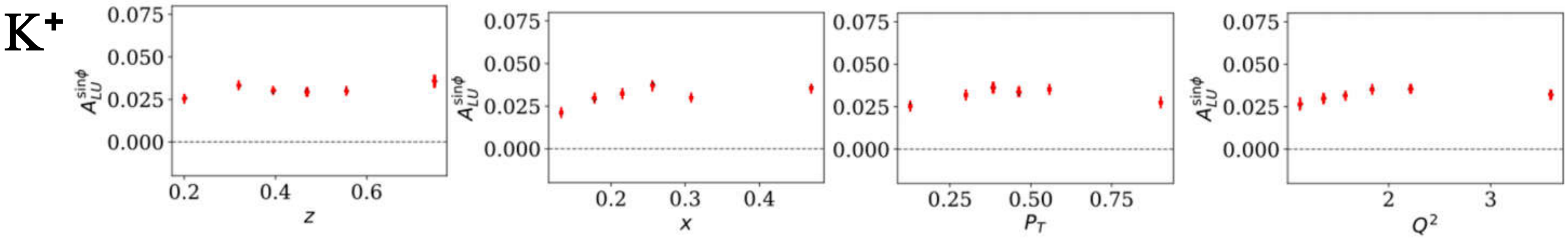
➔ TMD and Fragmentation Functions

$A_{LU}^{\sin(\phi)}$ measurement for π⁺, π⁻, π⁰ and K⁺ with CLAS



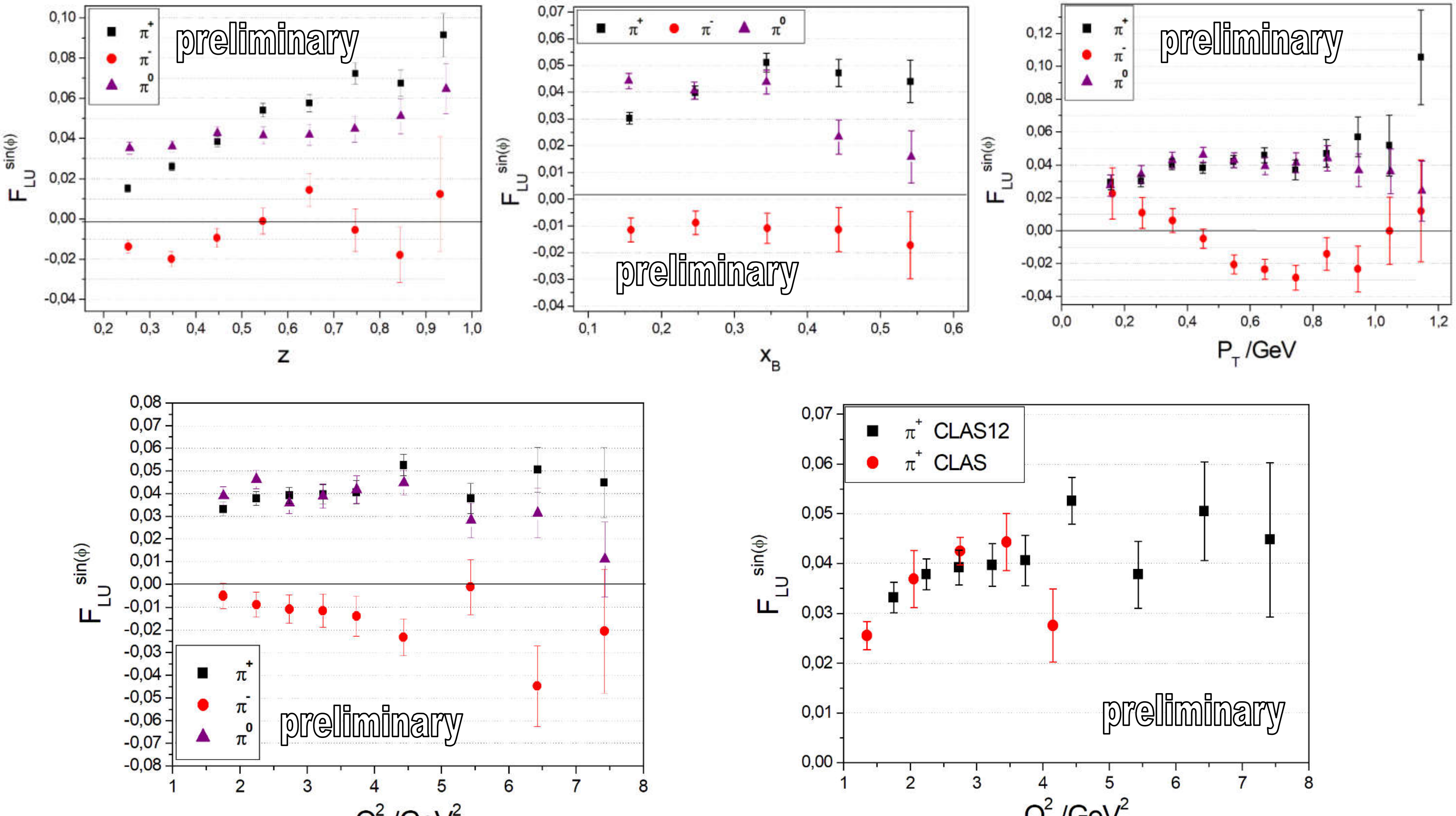
W. Gohn, Ph.D thesis (UConn)
Phys. Rev. D 89, 072011

Flavor dependences, and their understanding is important for interpretation of spin-azimuthal asymmetries



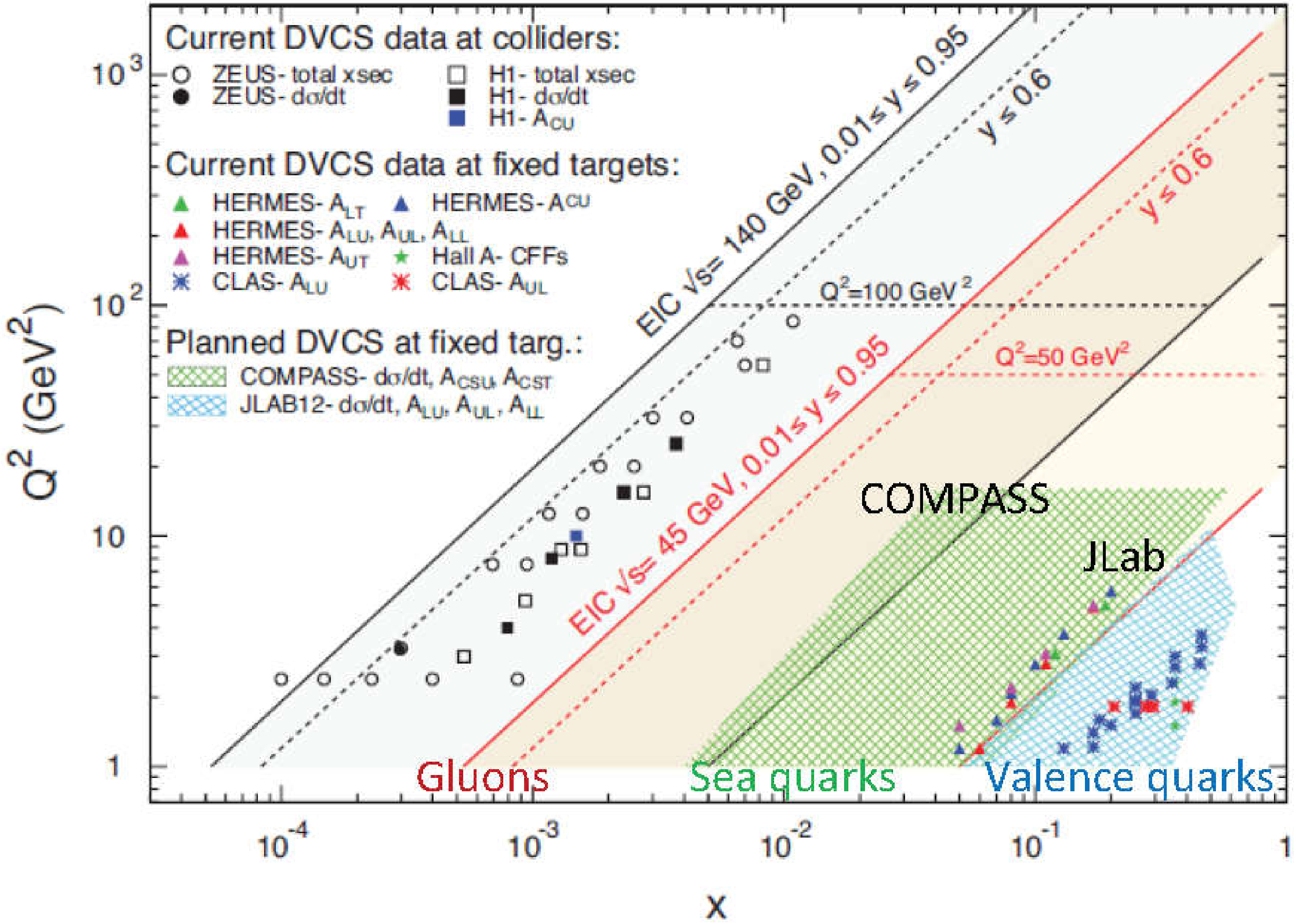
D. Riser, Ph.D thesis (UConn)

$F_{LU}^{\sin(\phi)}$ measurement for π^+, π^- and π^0 with CLAS12 (E_{beam} = 10.6 GeV)



S. Diehl (JLU + UConn)

Past, Present and Future 3-D Experiments



Summary

- TMDs and GPDs provide a unifying framework to study the 3-D quark and gluon structure of the nucleon

- 3-D imaging of nucleon will uncover rich dynamics of QCD

- Exciting time has just started with CLAS12 high precision and high statistics measurements with large kinematic coverages!