

# Studies of 3D PDFs with CLAS

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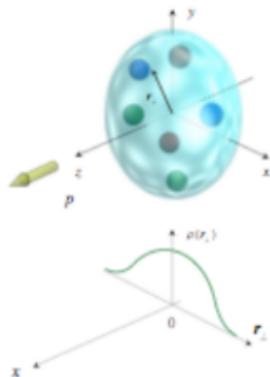
on behalf of CLAS collaboration

The Nature of Hadron Mass and Quark-Gluon Confinement  
from JLab Experiments in the 12-GeV Era  
July 3, 2018



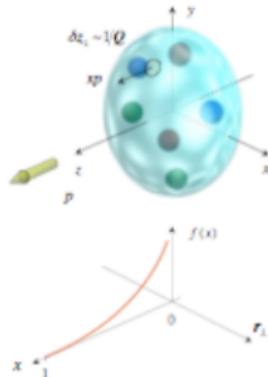
# Description of hadron structure

D. Müller, X. Ji, A. Radyushkin



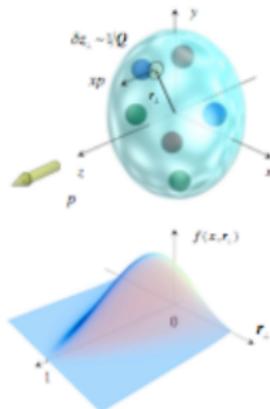
Nucleon Form Factors

transverse charge and  
current densities



Parton Distributions

quark longitudinal  
momentum distributions

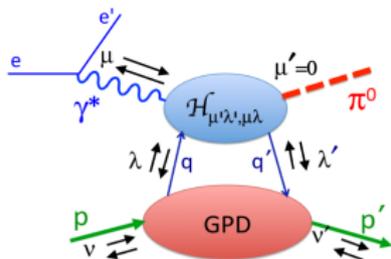


Generalized Parton  
Distributions (GPDs)

correlated quark momentum  
distributions in transverse  
space

# GPDs in Deeply Virtual Exclusive Production

- 4 parton helicity conserving (chiral even) GPDs:  $H$ ,  $\tilde{H}$ ,  $E$ ,  $\tilde{E}$
- 4 parton helicity flip (chiral odd) GPDs:  $H_T$ ,  $\tilde{H}_T$ ,  $E_T$ ,  $\tilde{E}_T$
- functions of three kinematic variables:  $x$ ,  $\xi$  and  $t$



- $$\langle F \rangle = \sum_{\lambda} \int_{-1}^1 dx \mathcal{H}_{0\lambda,\mu\lambda}(x, \xi, Q^2, t) F(x, \xi, t)$$

**Generalized Form Factor  $\langle F \rangle$**  is a convolution of hard subprocess with GPD  $F$

# Generalized Parton Distributions

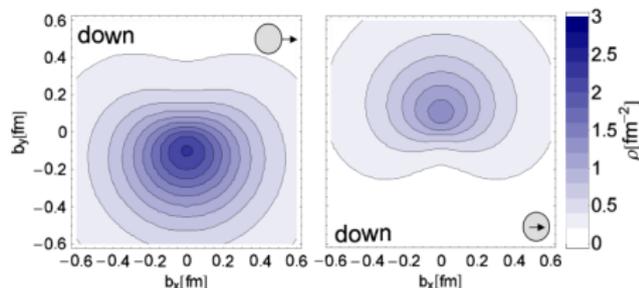
		Quark polarization		
		U	L	T
Nucleon polarization	U	$H$		$\bar{E}_T$
	L		$\tilde{H}$	
	T	$E$		$H_T, \tilde{H}_T$

Chiral-odd GPD results:

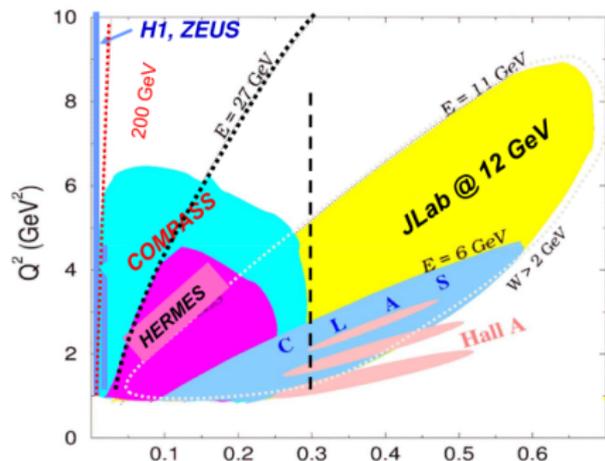
- Deeply Virtual Meson Production
- Lattice QCD by Gökeler *et al*

Chiral even GPDs:

- DVCS on unpolarized and polarized targets with polarized beam by HERMES, JLAB and COMPASS



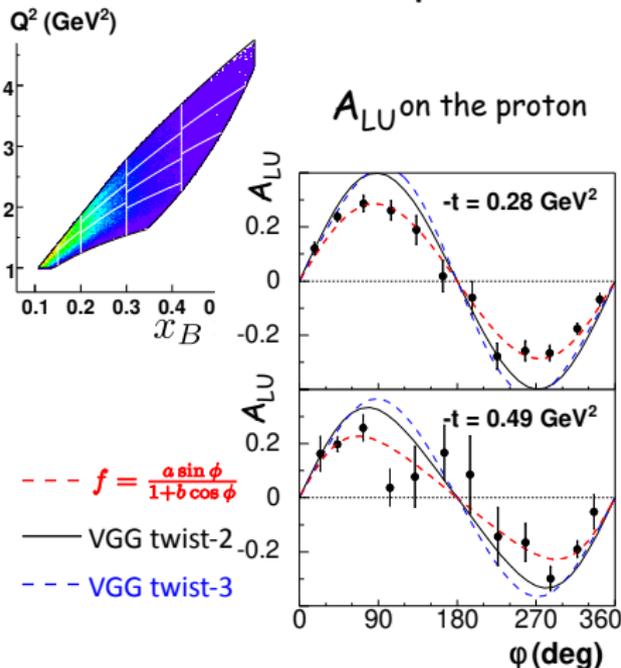
# Roadmap: from 6 GeV to 12 GeV



- Early results (2001) from non-dedicated experiment with CLAS (DVCS target spin asymmetry)
- First round of dedicated experiments in Halls A/B at JLab 2004/2005
- Second round of dedicated experiments 2008/2010
- Strong exclusive program at 12 GeV, data analysis from CLAS12 first experiment is ongoing

# DVCS beam spin asymmetries

## First round experiment at Hall B: E01-113

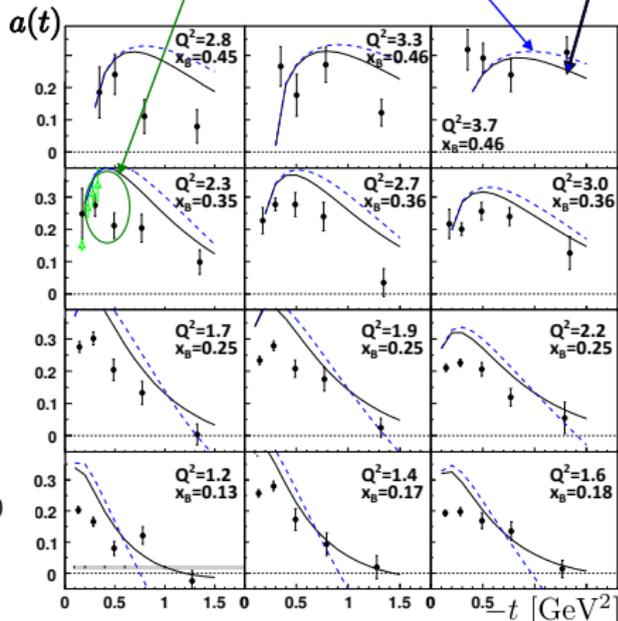


VGG model: Vanderhaeghen, Guichon, Guidal

JLab Hall A results

VGG twist-3

VGG twist-2

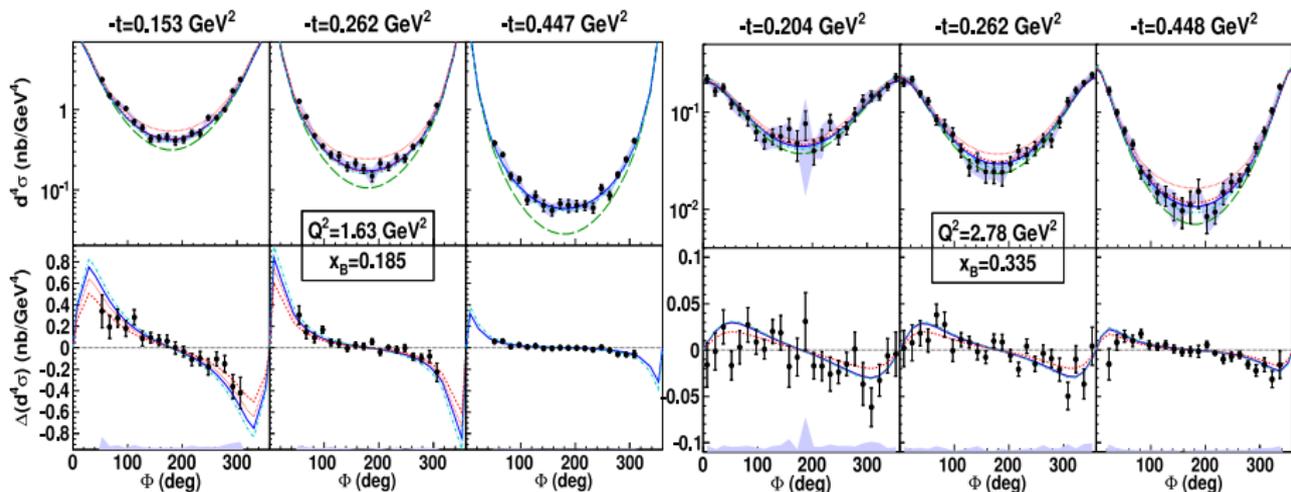


PRL100:162002 (2008) F.X. Girod *et al.* (CLAS collaboration)

## First round experiment at Hall B: E01-113

Measurements in a **LARGE** kinematic domain

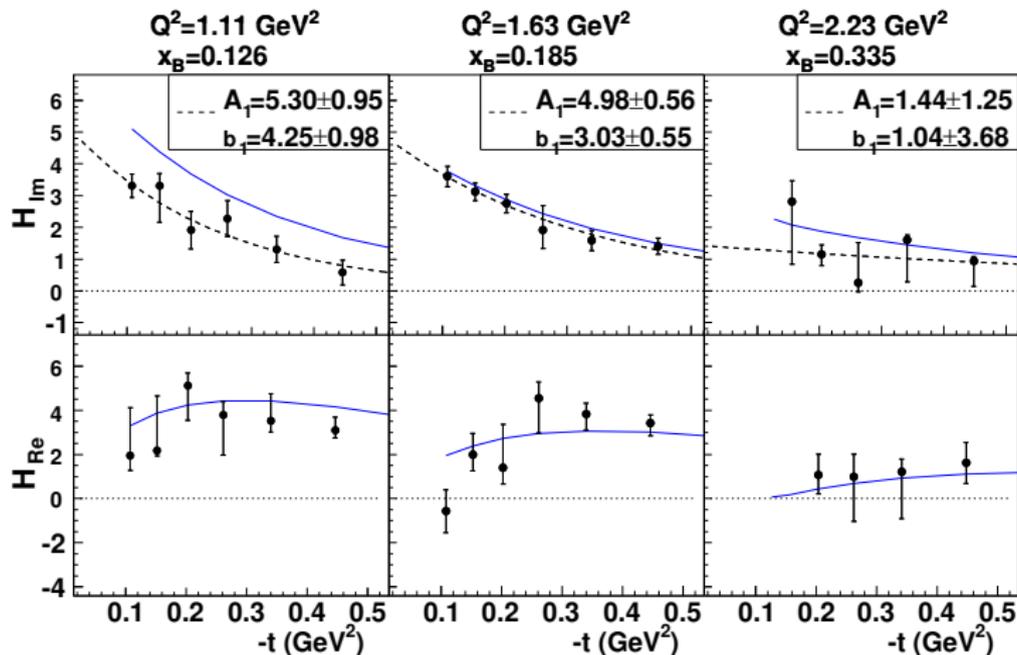
- KMS
- VGG
- ⋯ KM10 (Kumericki, Mueller)
- - KM10a



PRL115:212003 (2015) H.S. Jo *et al.* (CLAS collaboration)

First round experiment at Hall B: E01-113

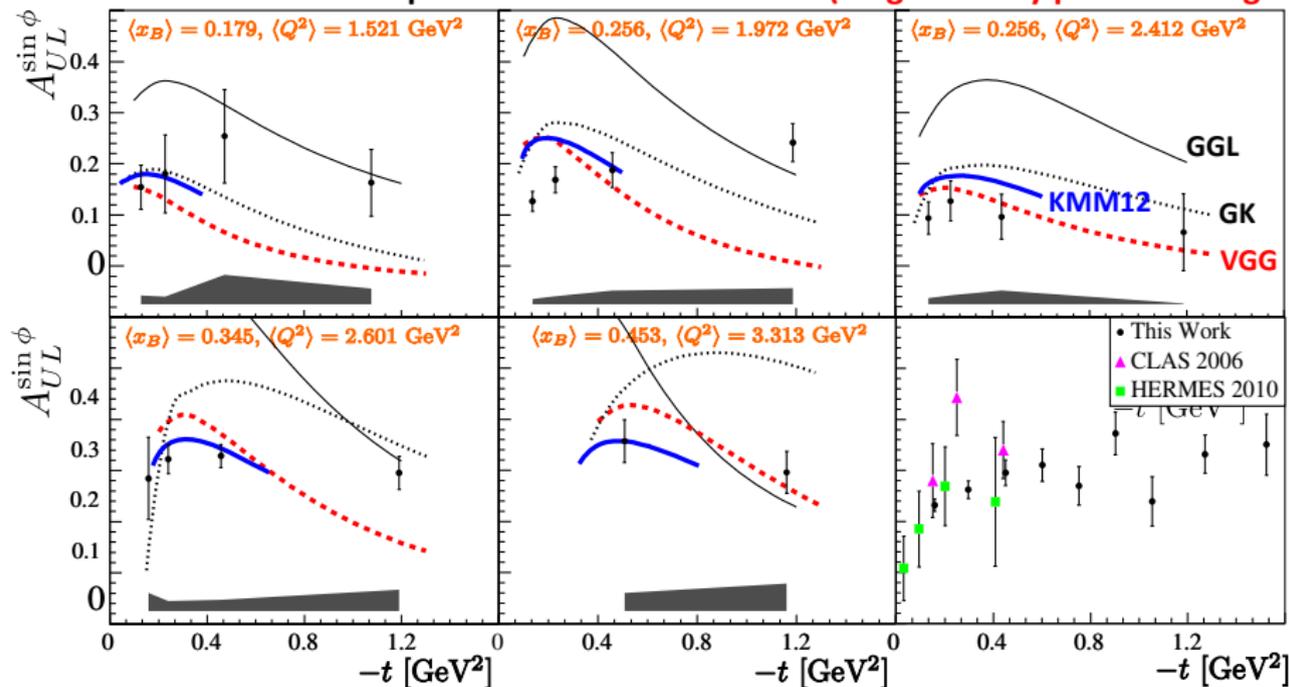
-- fit  $Ae^{bt}$   
 — VGG



PRL115:212003 (2015) H.S. Jo *et al.* (CLAS collaboration)

# DVCS target spin asymmetries

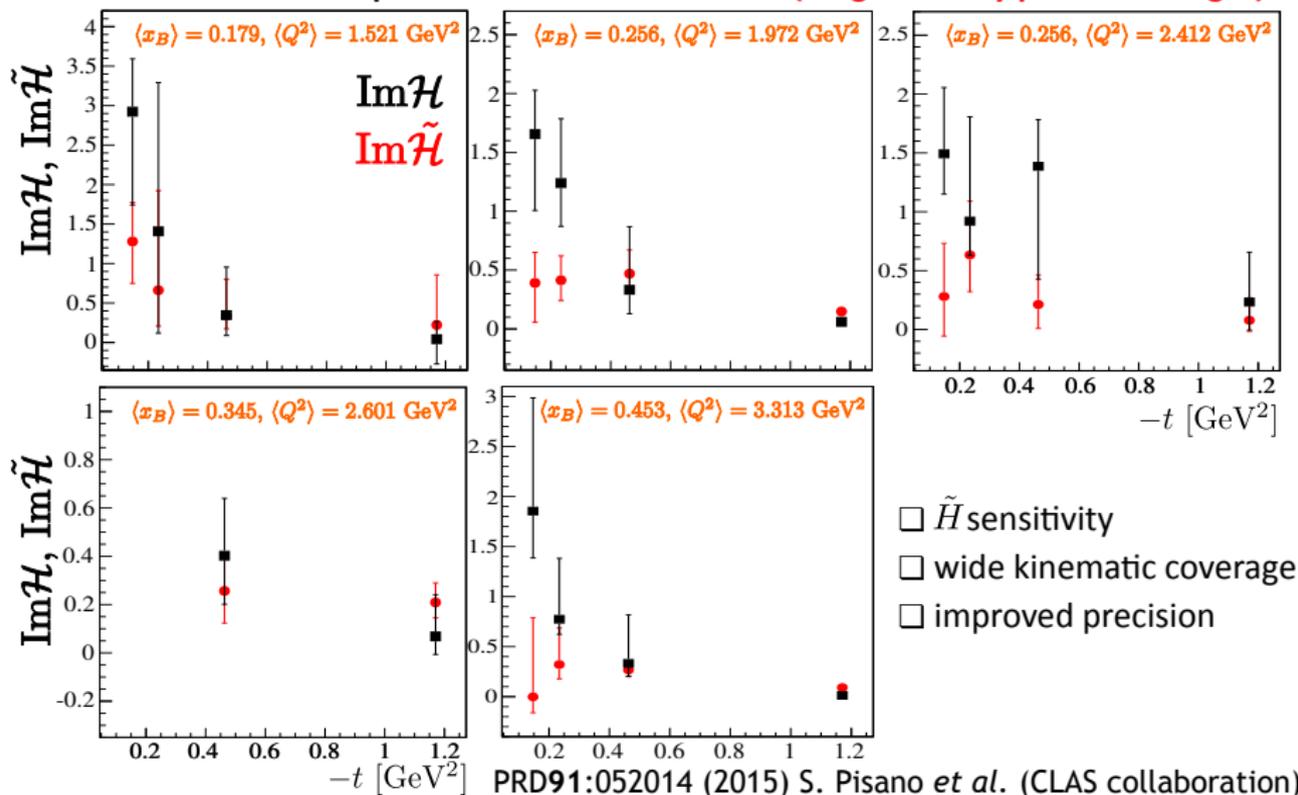
## Second round experiment at Hall B: E05-114 (longitudinally polarized target)



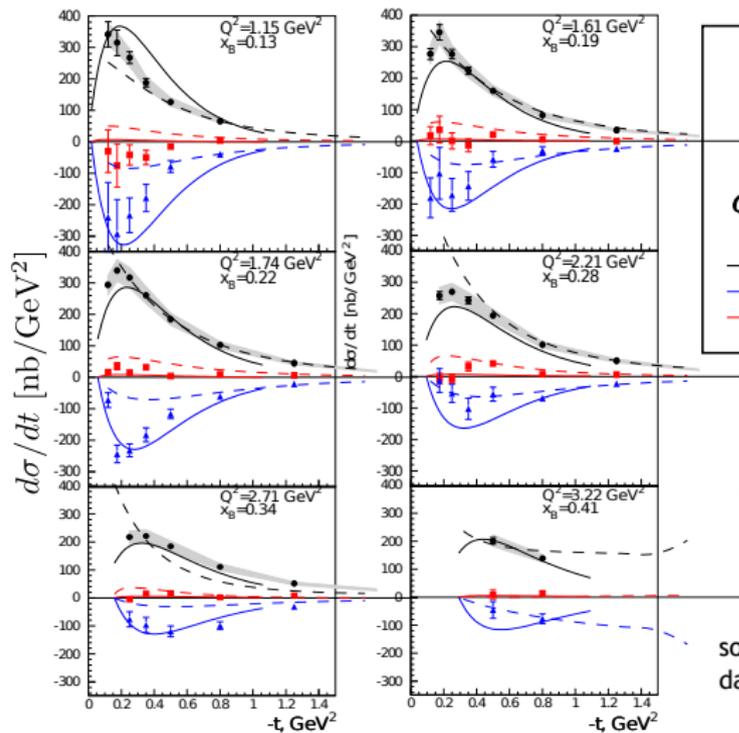
PRL114:032001 (2015) E. Seder *et al.* (CLAS collaboration)

# DVCS Compton form factors

## Second round experiment at Hall B: E05-114 (longitudinally polarized target)



# $\pi^0$ structure functions



Inclusion of the Chiral-odd GPDs brings theoretical calculations into moderate agreement with the data.

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

$$\text{--- } \sigma_0 = \sigma_T + \epsilon\sigma_L$$

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

$$\text{--- } \sigma_{LT}$$

## $\pi^0$ electroproduction

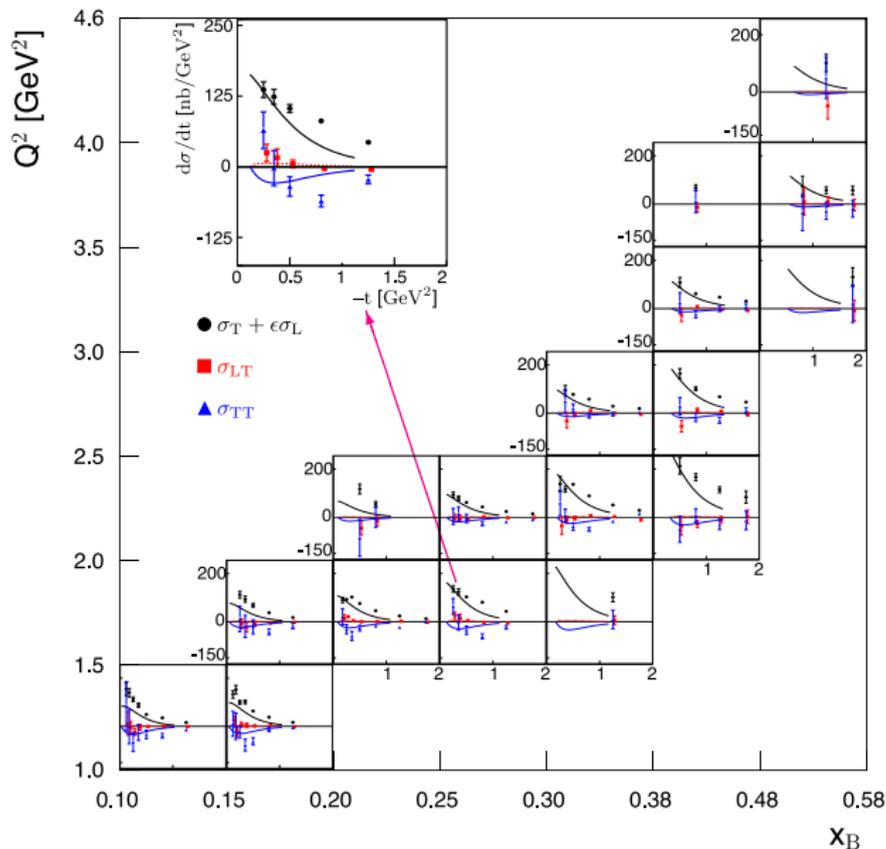
is uniquely sensitive process to access transversity GPDs.

solid: P.Kroll & S.Goloskokov

dashed: G.R. Goldstein, J.O. Gonzalez & S.Liuti

PRL109:112001 (2012) I. Bedlinskiy et al. (CLAS collaboration)

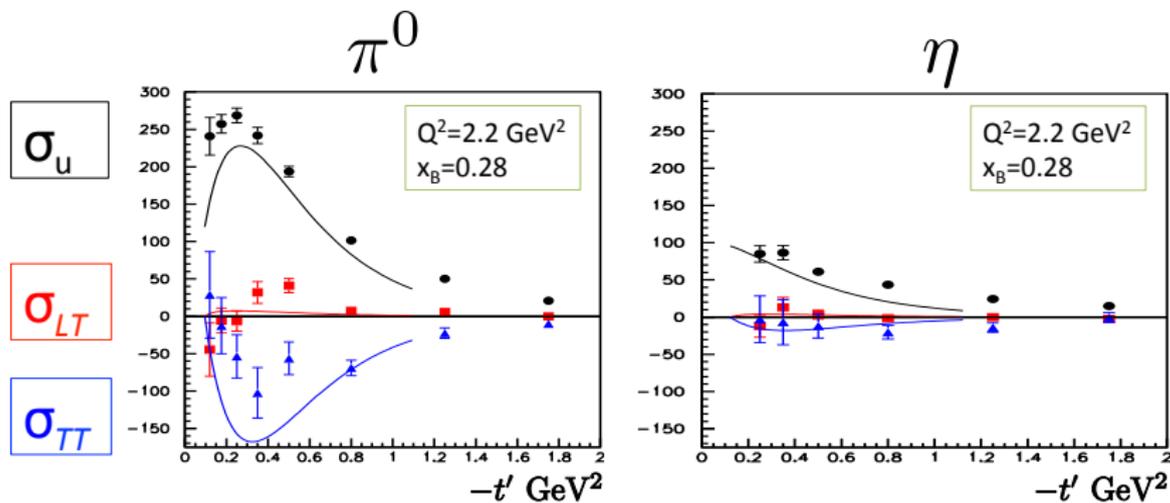
# $\eta$ structure functions



PRL95: 035202 (2017)

I. Bedlinsky et al. (CLAS)

# Comparison of $\pi^0$ and $\eta$



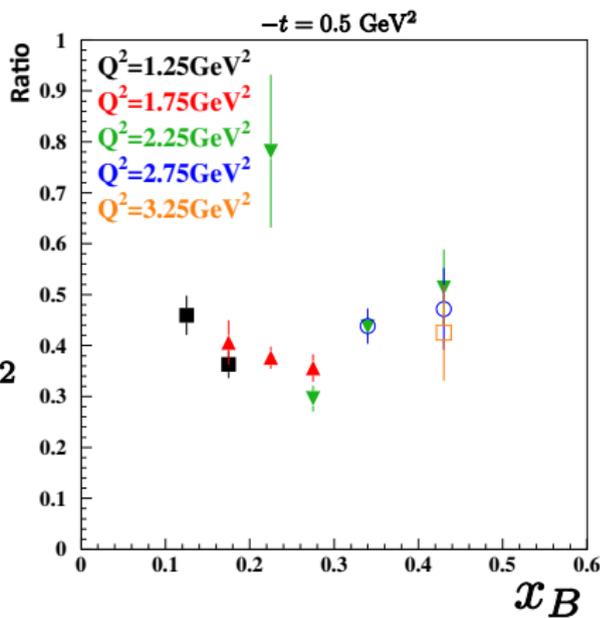
- $\sigma_U = \sigma_T + \epsilon\sigma_L$  drops by a factor of 2.5 for  $\eta$
- $\sigma_{TT}$  drops by a factor of 10
- Theoretical model calculations (GK model) follows the experimental measurements

# Ratio of $\pi^0$ and $\eta$

$$F_i^{\pi^0} = \frac{(e_u F_i^u - e_d F_i^d)}{\sqrt{2}}$$

$$F_i^{\eta} = \frac{(e_u F_i^u + e_d F_i^d)}{\sqrt{6}}$$

$$\frac{d\sigma(\eta)}{d\sigma(\pi^0)} \simeq \left(\frac{f_\eta}{f_\pi}\right)^2 \frac{1}{3} \left| \frac{2\langle F_T^u \rangle - \langle F_T^d \rangle}{2\langle F_T^u \rangle + \langle F_T^d \rangle} \right|^2$$



- Theoretical calculations based on chiral odd GPDs predict this ratio to be around 1/3 at CLAS kinematics

# Access to transverse GPDs

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

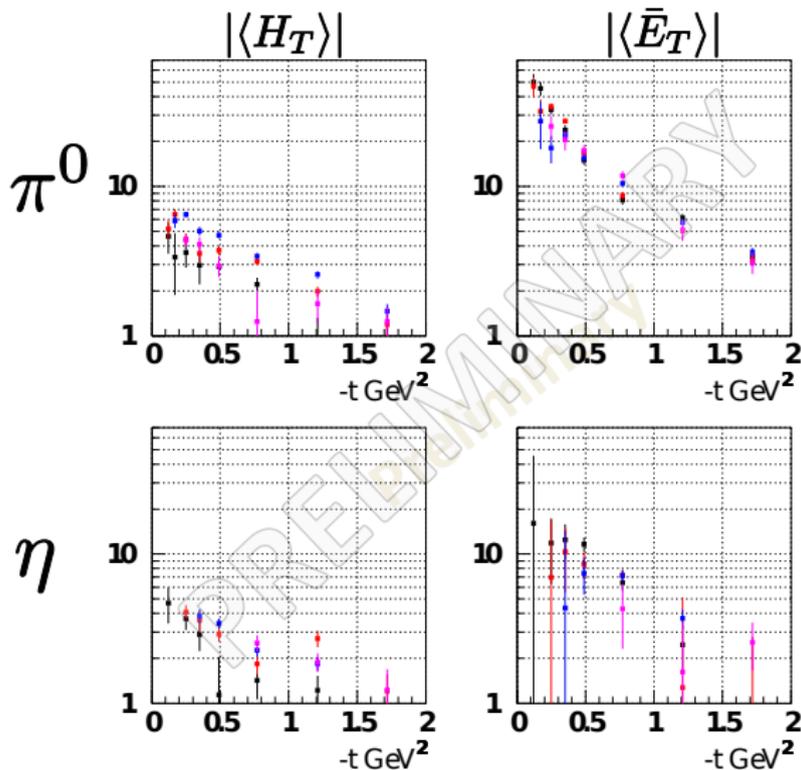
Goloskokov, Kroll  
Transversity GPD model



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

- No separation of  $\sigma_T$  and  $\sigma_L$
- However, in the approximation of transversity GPDs dominance, supported by JLab data,  $\sigma_L \ll \sigma_T$  and can be neglected

# Generalized Form Factors



$Q^2$ [GeV <sup>2</sup> ]	$\chi_B$
1.2	0.15
1.8	0.22
2.2	0.27
2.7	0.34

- $\bar{E}_T > H_T$  for both  $\pi^0$  and  $\eta$
- t-dependence is steeper for  $\bar{E}_T$

V. Kubarovsky, arXiv:1601.04367

# Flavor decomposition

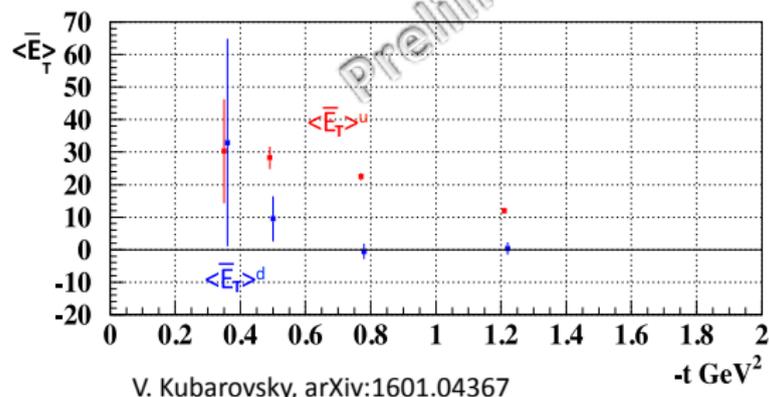
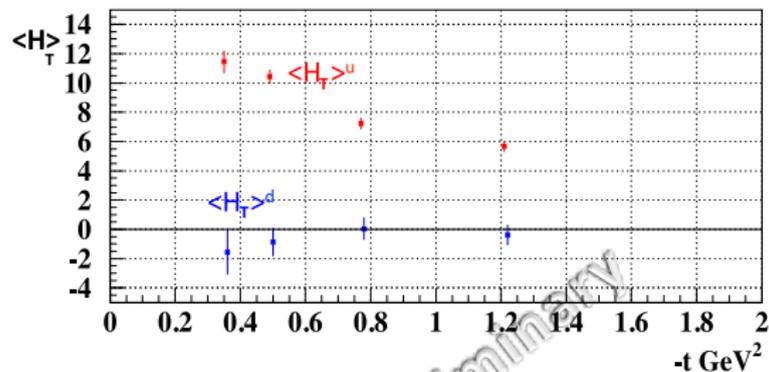
$$F^\pi = \frac{1}{3\sqrt{2}} [2F^u + F^d]$$
$$F^\eta = \frac{1}{3\sqrt{6}} [2F^u - F^d]$$



$$\frac{1}{18} |2\langle H_T \rangle^u + \langle H_T \rangle^d|^2 = |\langle H_T \rangle^\pi|^2$$
$$\frac{1}{54} |2\langle H_T \rangle^u - \langle H_T \rangle^d|^2 = |\langle H_T \rangle^\eta|^2$$

- GPDs appear in different flavor combinations for  $\pi^0$  and  $\eta$
- **Combined datasets of  $\pi^0$  and  $\eta$  channels** allow flavor decomposition for GPDs  $H_T$  and  $\bar{E}_T$
- To attempt flavor decomposition an assumption on the relative phase between  $u$  and  $d$  quark GPDs was made to be either 0 or 180 degrees.

# First attempts at flavor decomposition



V. Kubarovsky, arXiv:1601.04367

$$Q^2 = 1.8 \text{ GeV}^2$$

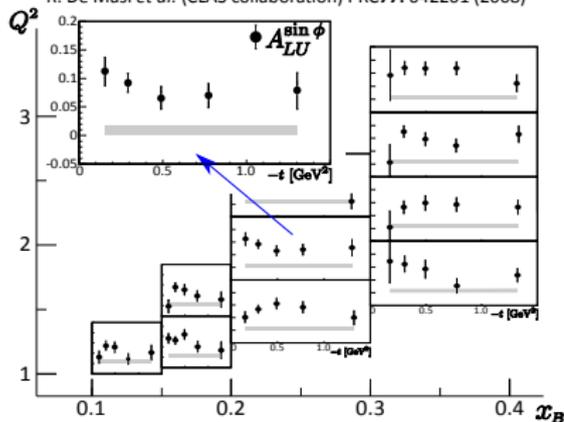
$$x_B = 0.22$$

- $\langle H_T \rangle^u$  and  $\langle H_T \rangle^d$  have opposite signs in accordance with transversity function  $h_1$  (Anselmino *et al.*)
- $\langle E_T \rangle^u$  and  $\langle E_T \rangle^d$  have the same signs

# Spin asymmetry variables

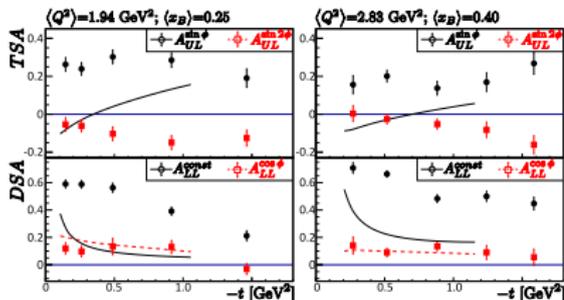
## $\pi^0$ Beam Spin Asymmetries

R. De Masi *et al.* (CLAS collaboration) PRC77: 042201 (2008)

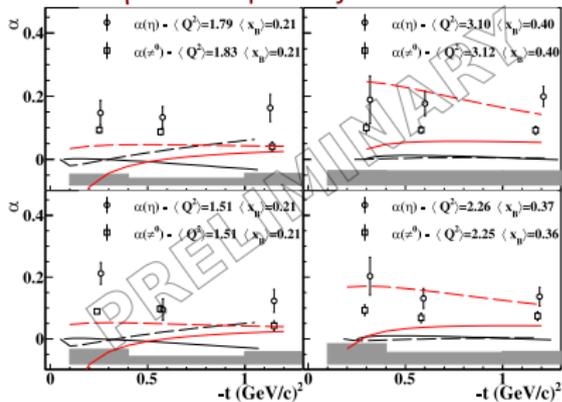


## $\pi^0$ Target and Double Spin Asymmetries

A. Kim *et al.* (CLAS) PLB768, 168-173 (2017)



## $\eta$ Beam Spin Asymmetries



- Large number of single and double spin asymmetries were measured over wide kinematic range
- Asymmetries are much harder to interpret since they involve convolutions of chiral even and chiral odd GPDs

# 12 GeV upgrade and CLAS12

## Forward Detector (FD)

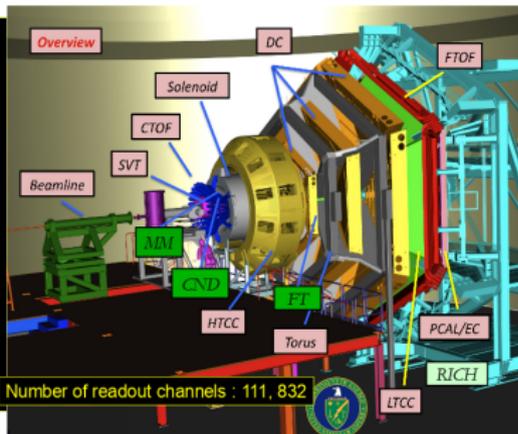
TORUS magnet  
HT Cherenkov Counter  
Drift chamber system  
LT Cherenkov Counter  
Forward ToF System  
Pre-shower calorimeter  
E.M. calorimeter  
Forward Tagger  
RICH detector

## Central Detector (CD)

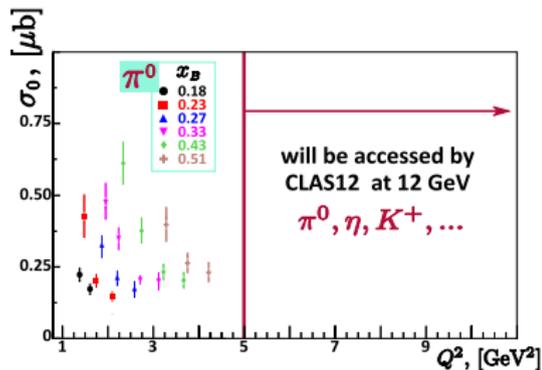
Solenoid magnet  
Silicon Vertex Tracker  
Central Time-of-Flight  
Central Neutron Det.  
MicroMegas

## Beamline

Photon Tagger  
Shielding  
Polarized Targets



- DVCS/DVMP( $\pi^0, \eta, \dots$ ):
  - at 6.6, 8.8 and 11 GeV
  - on proton and neutron at 11 GeV



# Approved Experiments

- **E12-06-119:** Deeply Virtual Compton Scattering with CLAS at 11 GeV
- **E12-06-108:** Hard Exclusive Electroproduction of  $\pi^0$  and eta with CLAS12
- **E12-11-003:** Deeply Virtual Compton Scattering on the Neutron with CLAS12 at 11 GeV
- **E12-12-007:** Exclusive Phi Meson Electroproduction with CLAS12
- **E12-06-109A:** Deeply Virtual Compton scattering on the neutron with a longitudinally polarized deuteron target
- **E12-16-010B:** Deeply Virtual Compton Scattering with CLAS12 at 6.6 GeV and 8.8 GeV

# Summary

- Deeply Virtual Compton Scattering provides access to the chiral even GPDs
- Deeply Virtual  $\pi^0$  and  $\eta$  electroproduction are sensitive to the chiral odd GPDs
- The measured structure functions are directly connected to the generalized form factors  $\langle H_T \rangle$  and  $\langle \bar{E}_T \rangle$
- The global analysis of DVCS,  $\pi^0$  and  $\eta$  production as well as data with neutron target, and inclusion of kaon production, will allow the flavor decomposition of transversity GPDs
- Awaiting new results at wider kinematic range from CLAS12 first experiment

STAY TUNED FOR 12 GeV DATA!