Exclusive Meson Production with CLAS/CLAS12 and Transversity GPDs

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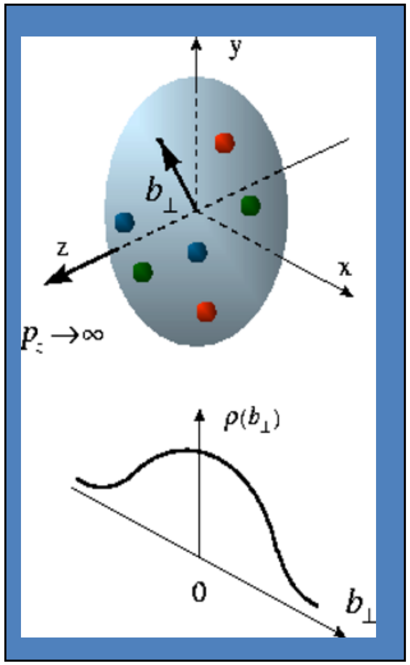
Outline

- Physics motivation
- Measurements on hard exclusive pseudo-scaler meson electroproduction with CLAS
- Structure functions and transversity GPDs
- Flavor decomposition of the transversity GPDs
- GPD programs with CLAS12
- Summary

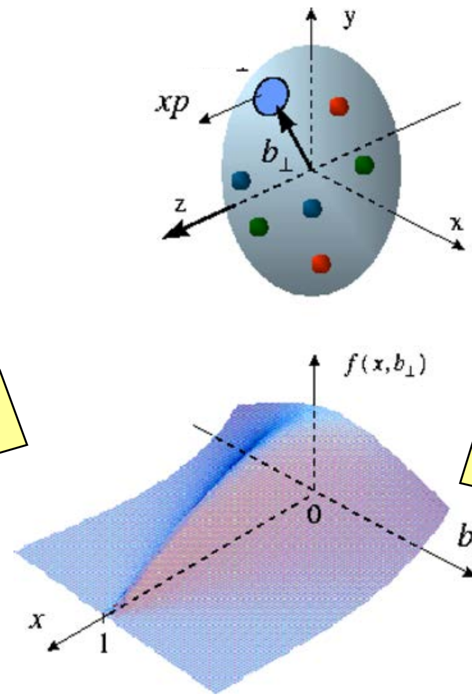
Generalized Parton Distributions and 3D Quark Imaging

Last 50 years



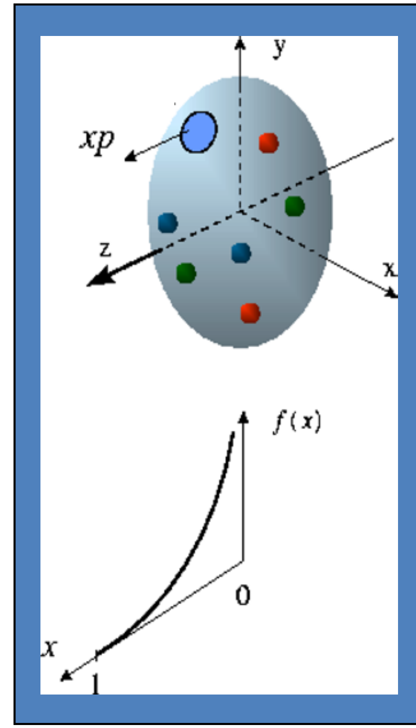
Proton form factors, transverse charge & current densities

Last 10 years



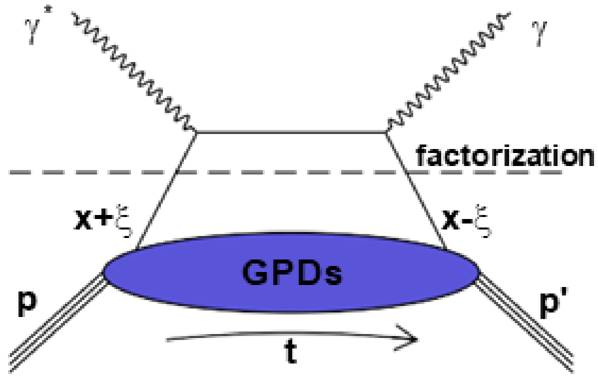
Correlated quark momentum and helicity distributions in transverse space - GPDs

Last 40 years



Structure functions, quark longitudinal momentum & spin distributions

Generalized Parton Distributions



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

The GPDs depend on three kinematic variables:

e.g. $F^q(x, \xi, t)$

x

average parton momentum fraction

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

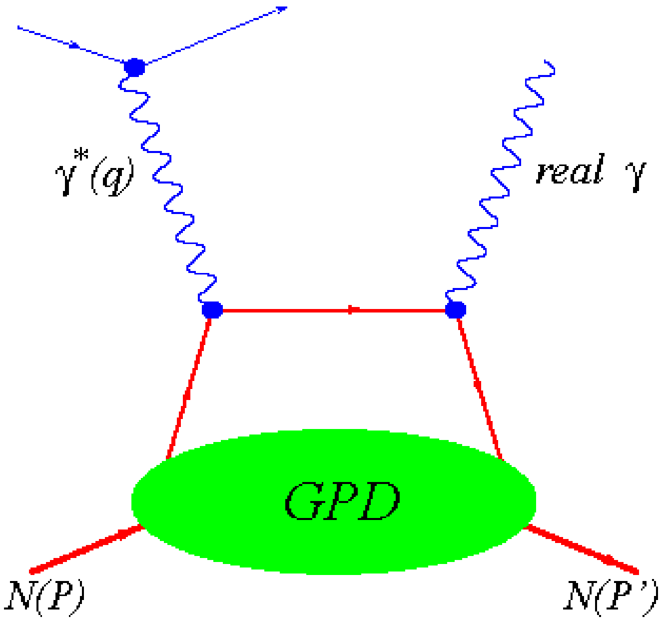
(skewness) difference between the initial and final fractions of the longitudinal momentum carried by the struck parton

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

momentum transfer between initial and final nucleons

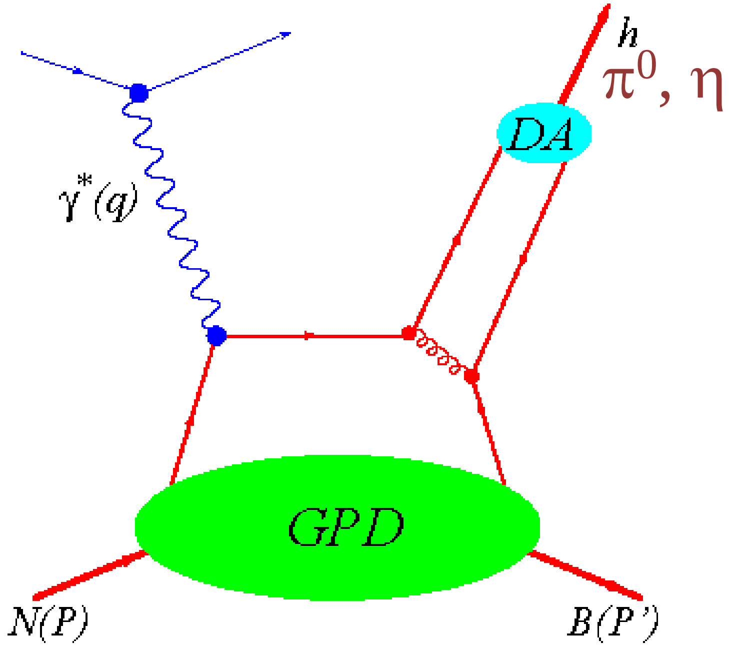
Deeply Virtual Exclusive Processes

Deeply Virtual Compton Scattering (DVCS)



H, H̃, E, Ẽ

Deeply Virtual Meson Production (DVMP)



H_T, $\tilde{H}_T$, E_T, $\tilde{E}_T$

Chiral-odd GPDs

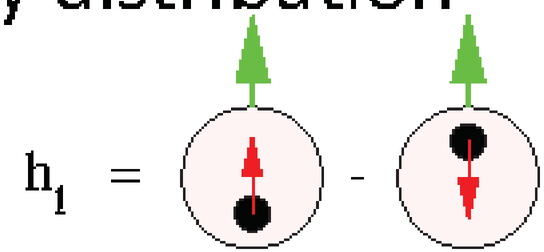
- Very little known about the chiral-odd GPDs
- Anomalous tensor magnetic moment

$$\kappa_T = \int_{-1}^{+1} dx\ \bar{E}_T(x,\xi,t=0) \qquad \bar{E}_T = 2\tilde{H}_T + E_T$$

- (Compare with anomalous magnetic moment)

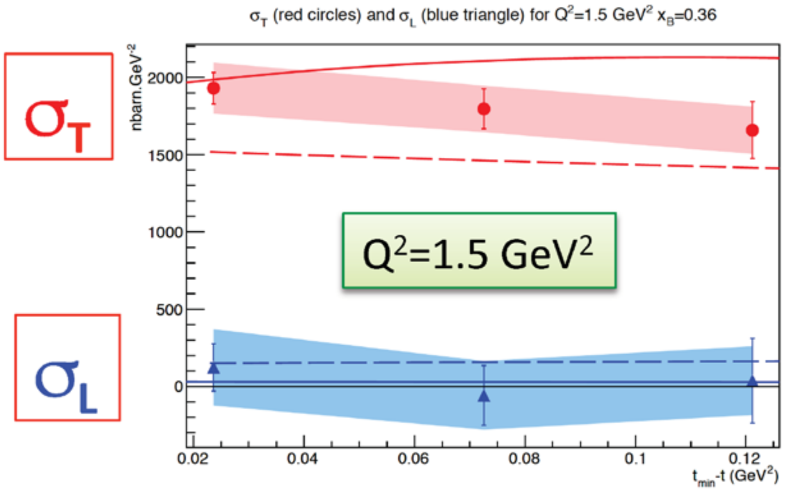
$$\kappa = \int_{-1}^{+1} dx\ E(x,\xi,t=0) = F_2(t=0)$$

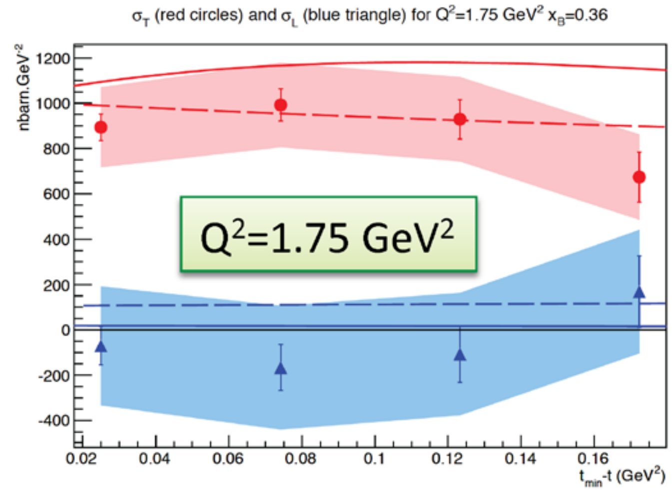
- Transversity distribution $\quad H_T^q(x,0,0) = h_1^q(x)$

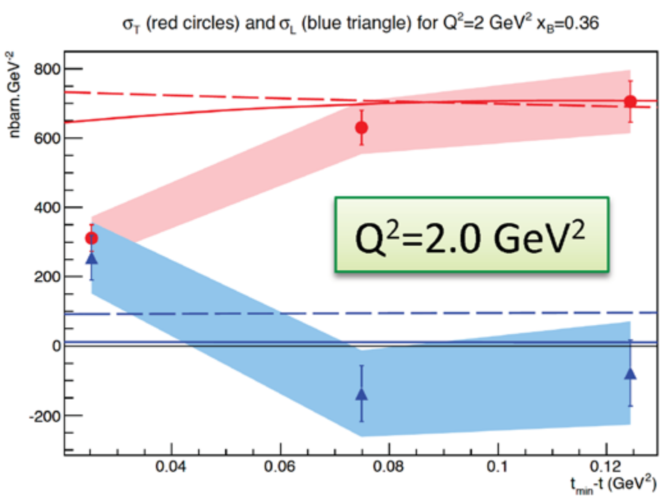


The transversity describes the distribution of transversely polarized quarks in a transversely polarized nucleon

Rosenbluth separation σ_T and σ_L
Hall-A Jefferson Lab







- Experimental **proof** that the transverse π^0 cross section is dominant!
- It opens the direct way to study the transversity GPDs in pseudoscalar exclusive production

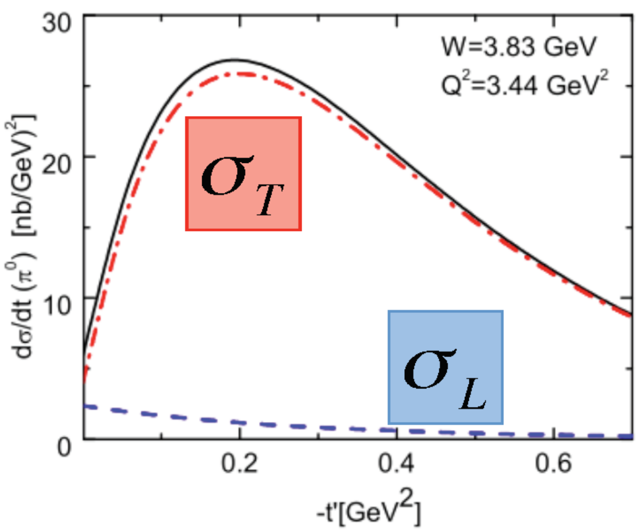
Hall-A, Phys.Rev.Lett. **117**,262001(2016)

Structure Functions and Transversity GPDs

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}(\sigma_T + \epsilon\sigma_L + \epsilon\cos 2\phi_\pi \sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \sigma_{LT})$$

$$\sigma_T = \frac{4\pi\alpha_e}{2\kappa}\frac{\mu_\pi^2}{Q^4}\left[(1-\xi^2)|\langle H_T\rangle|^2 - \frac{t'}{8m^2}|\langle \bar{E}_T\rangle|^2\right]$$

$$\sigma_{TT} = \frac{4\pi\alpha_e}{2\kappa}\frac{\mu_\pi^2}{Q^4}\frac{t'}{8m^2}|\langle \bar{E}_T\rangle|^2$$



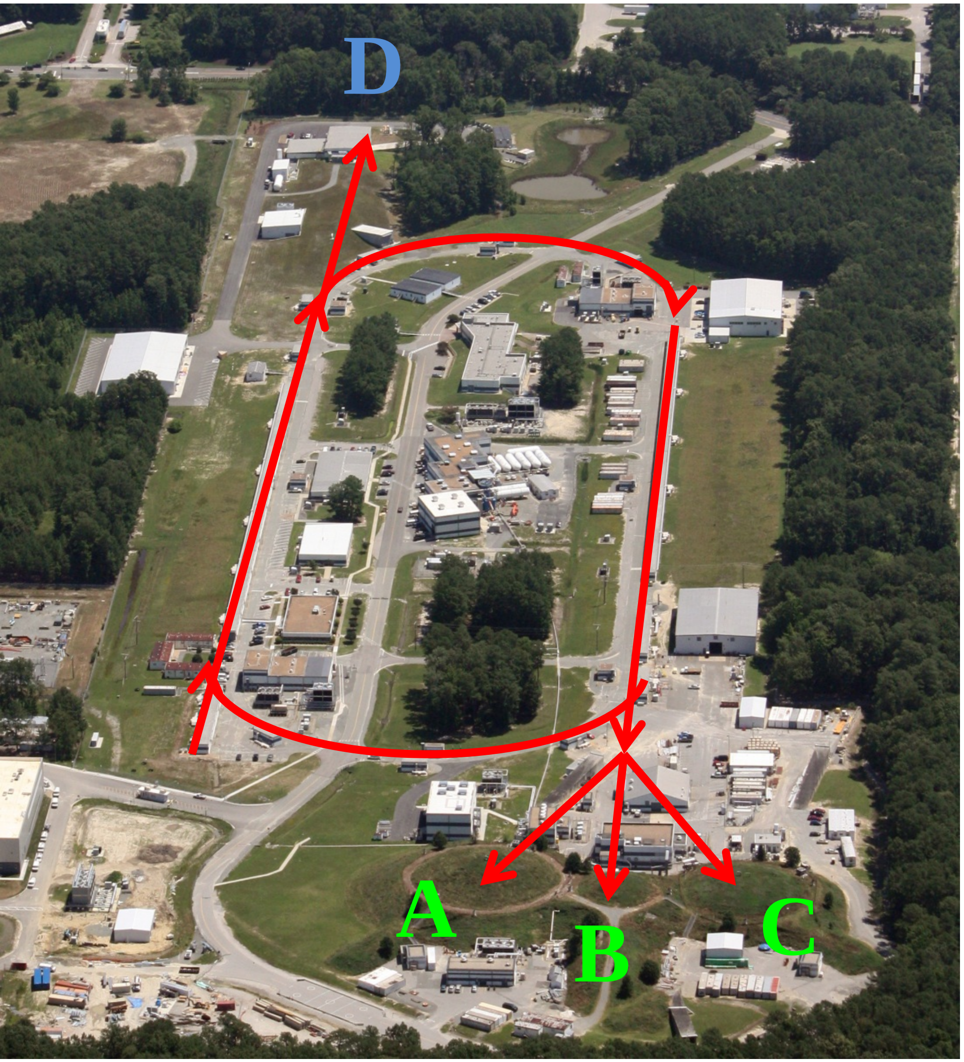
Transversity GPD model

S. Goloskokov and P. Kroll

S. Liuti and G. Goldstein

- $\sigma_L << \sigma_T$
- t-dependence at $t=t_{min}$ is determined by the interplay between H_T and $\bar{E}_T = 2\tilde{H}_T + E_T$

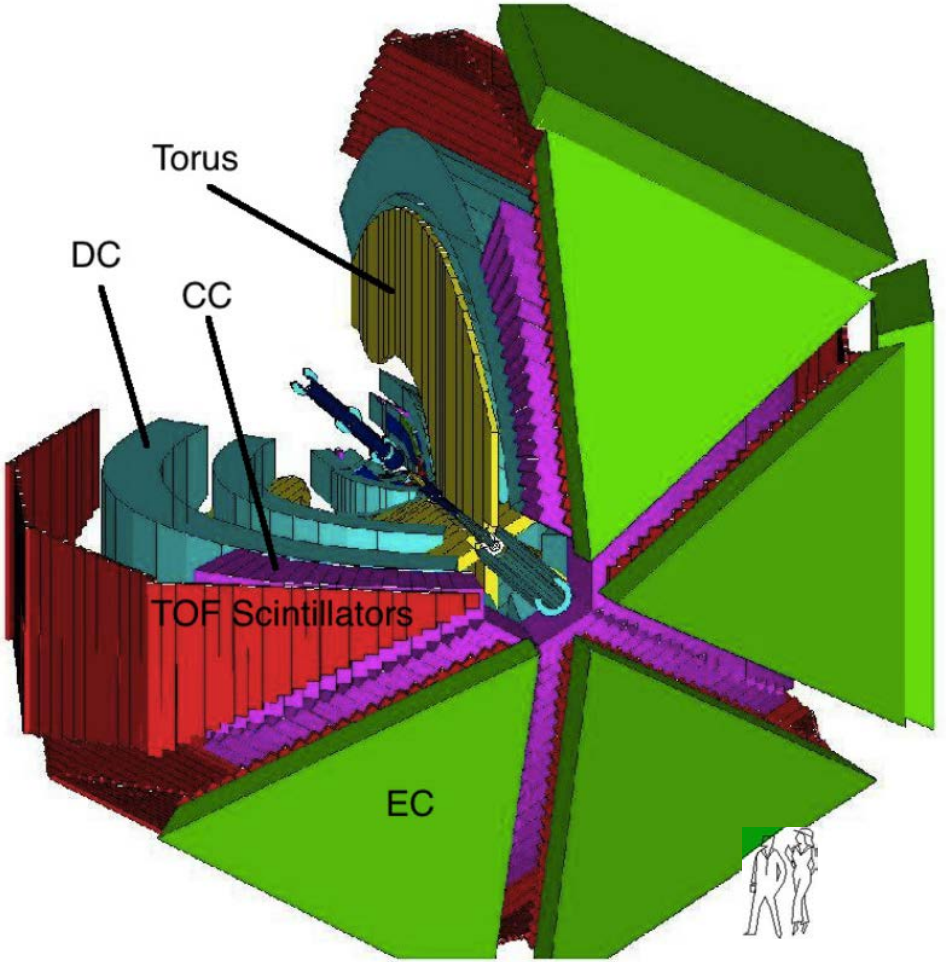
Thomas Jefferson National Accelerator Facility (Jefferson Lab)



Site Aerial, June 2012

- Superconducting RF electron linacs with up to 5X recirculation
- CW (100% duty factor) operation
- Polarized source: up to 85% polarization
- Three experimental Halls
- Energy up to 6 GeV (upgrade will increase to 11(12) GeV to Halls A/B/C (D))

CEBAF Large Acceptance Spectrometer (CLAS) in Hall B



- Electromagnetic Calorimeter (EC) and Čerenkov Counter (CC) used in electron identification.
- Drift Chamber (DC) (3 regions) and time of flight Scintillators (SC) record position and timing information for each charged track.
- Torus magnet creates toroidal magnetic field which causes charged tracks to curve whilepreserving the φlab angle.

Deeply Virtual Meson Production (DVMP)

unpolarized terms

$$\frac{2\pi}{\Gamma}\frac{d^4\sigma}{dQ^2dx_Bdtd\phi_\pi} = \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}\cos 2\phi + \sqrt{\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi$$

longitudinally polarized beam

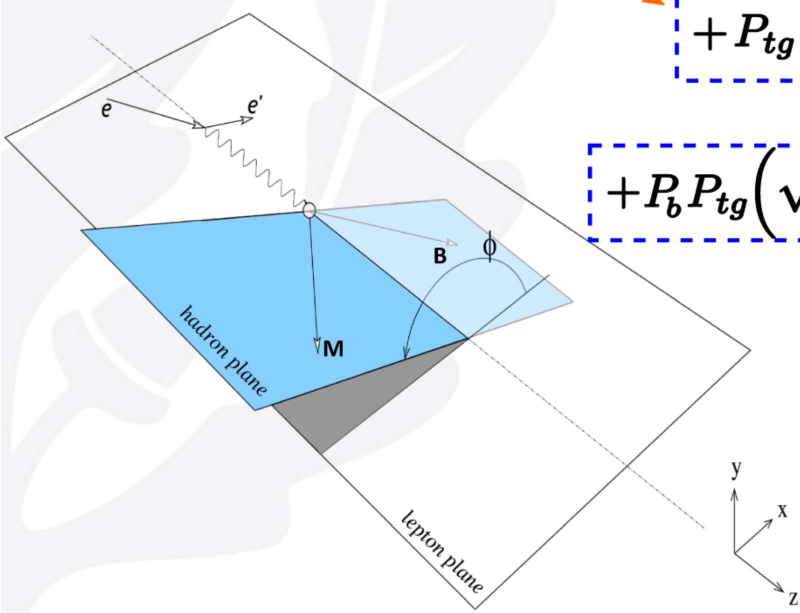
$$+P_b\sqrt{\epsilon(1-\epsilon)}\sigma_{LT'}\sin\phi$$

longitudinally polarized target

$$+P_{tg}\left(\sqrt{\epsilon(1+\epsilon)}\sigma_{UL}^{\sin\phi}\sin\phi + \epsilon\sigma_{UL}^{\sin 2\phi}\sin 2\phi\right)$$

$$+P_bP_{tg}\left(\sqrt{1-\epsilon^2}\sigma_{LL} + \sqrt{\epsilon(1-\epsilon)}\sigma_{LL}^{\cos\phi}\cos\phi\right)$$

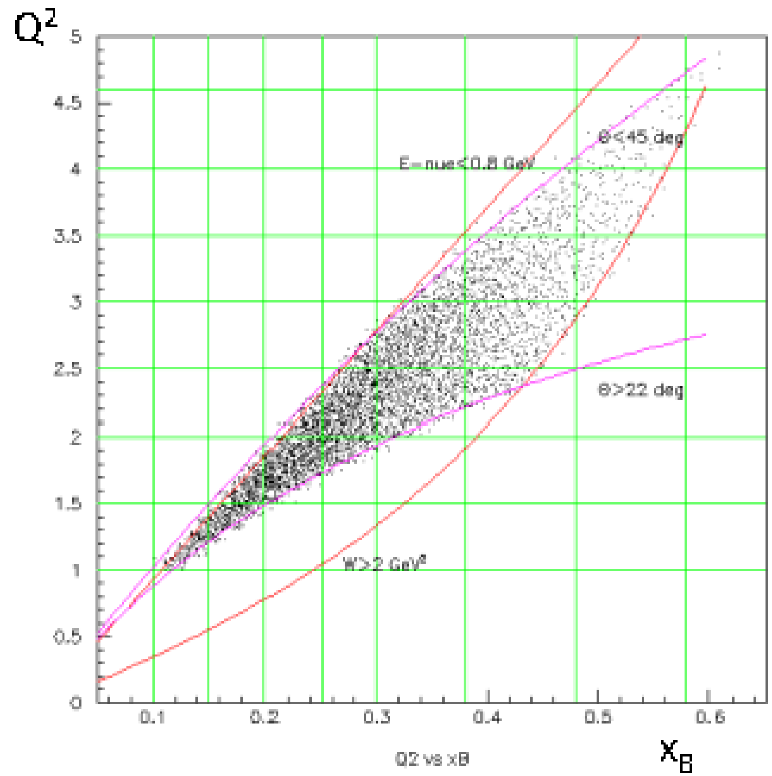
longitudinally polarized beam
and
longitudinally polarized target

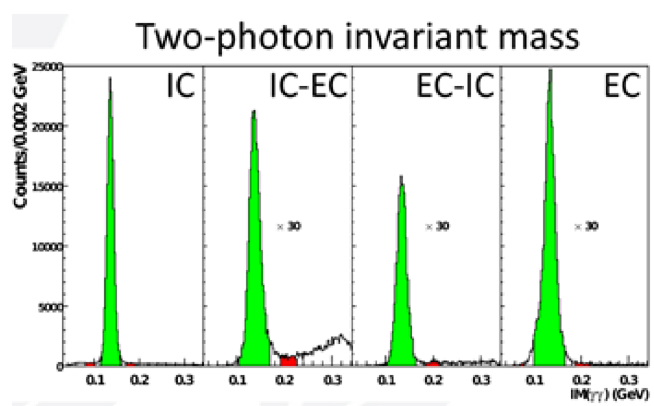


Differential Cross Sections $ep \rightarrow ep\pi^0$

Rectangular bins are used.

- Q^2 7 bins(1.-4.5GeV^2)
- x_B 7 bins(0.1-0.58)
- t 8 bins(0.09-2.0GeV)
- ϕ 20 bins(0-360°)
- π^0 data ~2000 points
- η data ~1000 points

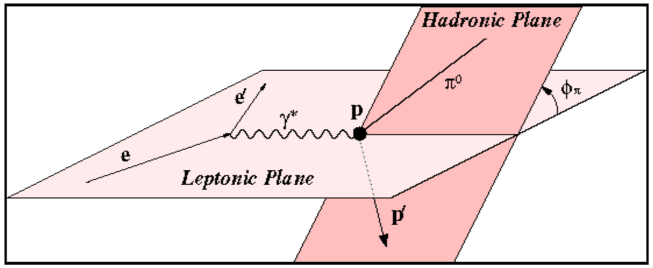




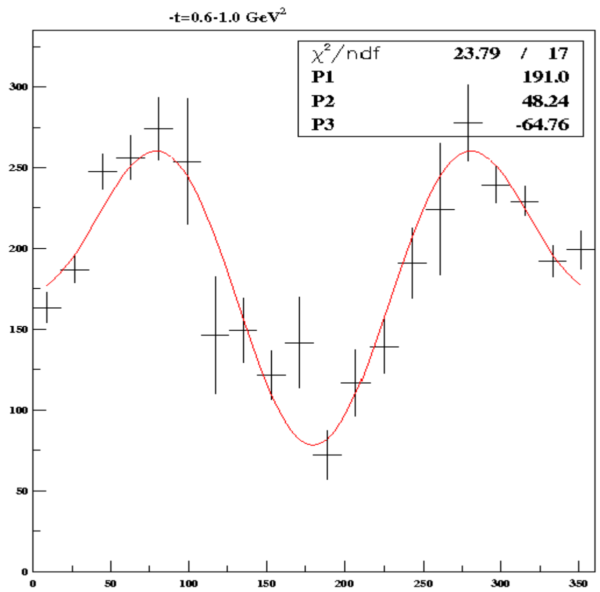
Differential Cross Sections $ep \to ep\pi^0$

Structure Functions

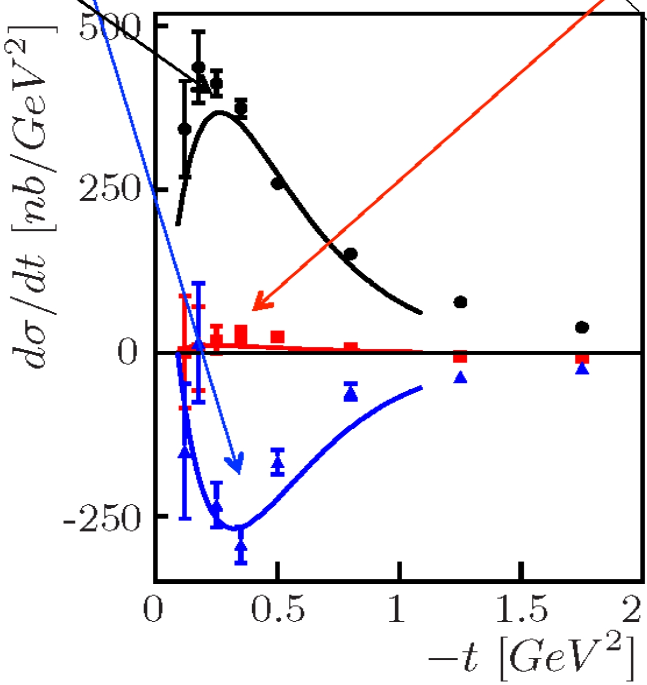
$\sigma_U = \sigma_T + \varepsilon\sigma_L \quad \sigma_{TT} \quad \sigma_{LT}$



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



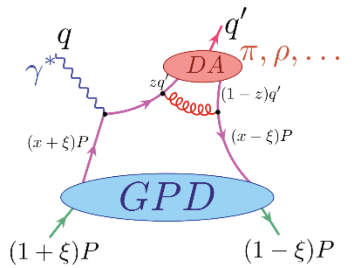
ϕ distribution

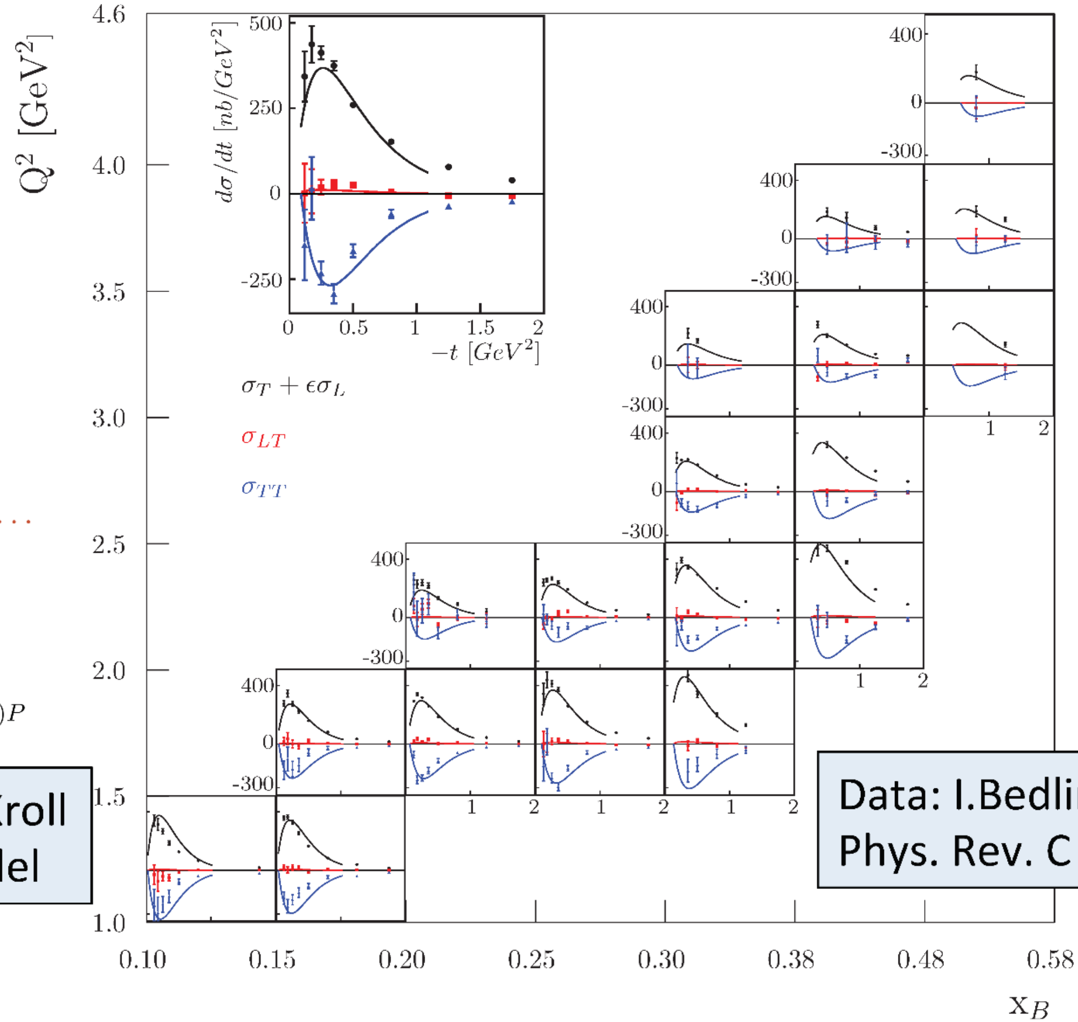


Structure Functions

$(\sigma_T + \varepsilon\sigma_L)$ σ_{TT} σ_{LT}

$\gamma^* p \to p\pi^0$





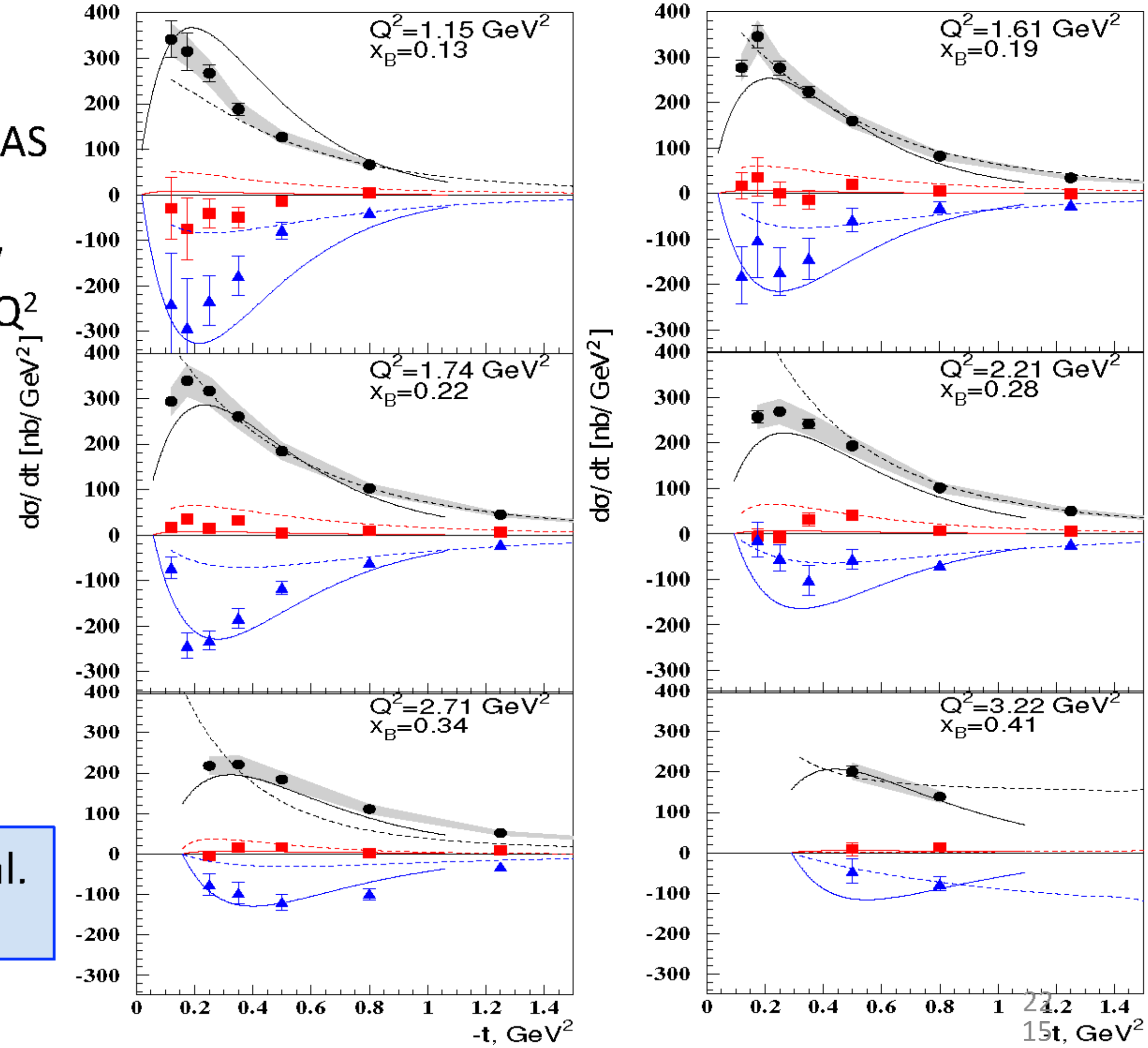
Curves: Goloskokov, Kroll
Transversity GPD model

Data: I.Bedlinskiy et al. (CLAS)
Phys. Rev. C 90, 039901 (2014)

CLAS data and GPD theory predictions

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

- ***Transversity* GPDs** H_T and $\bar{E}_T = 2\tilde{H}_T + E_T$ dominate in CLAS kinematics.
- The model was optimized for low x_B and high Q^2. The corrections t/Q^2 were omitted
- The model successfully describes CLAS data even at low Q^2
- Pseudoscalar meson production [provides unique possibility to access the transversity GPDs.]

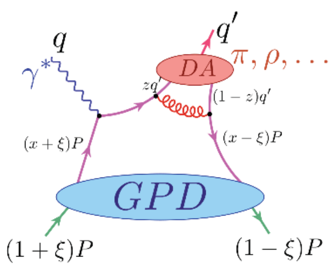


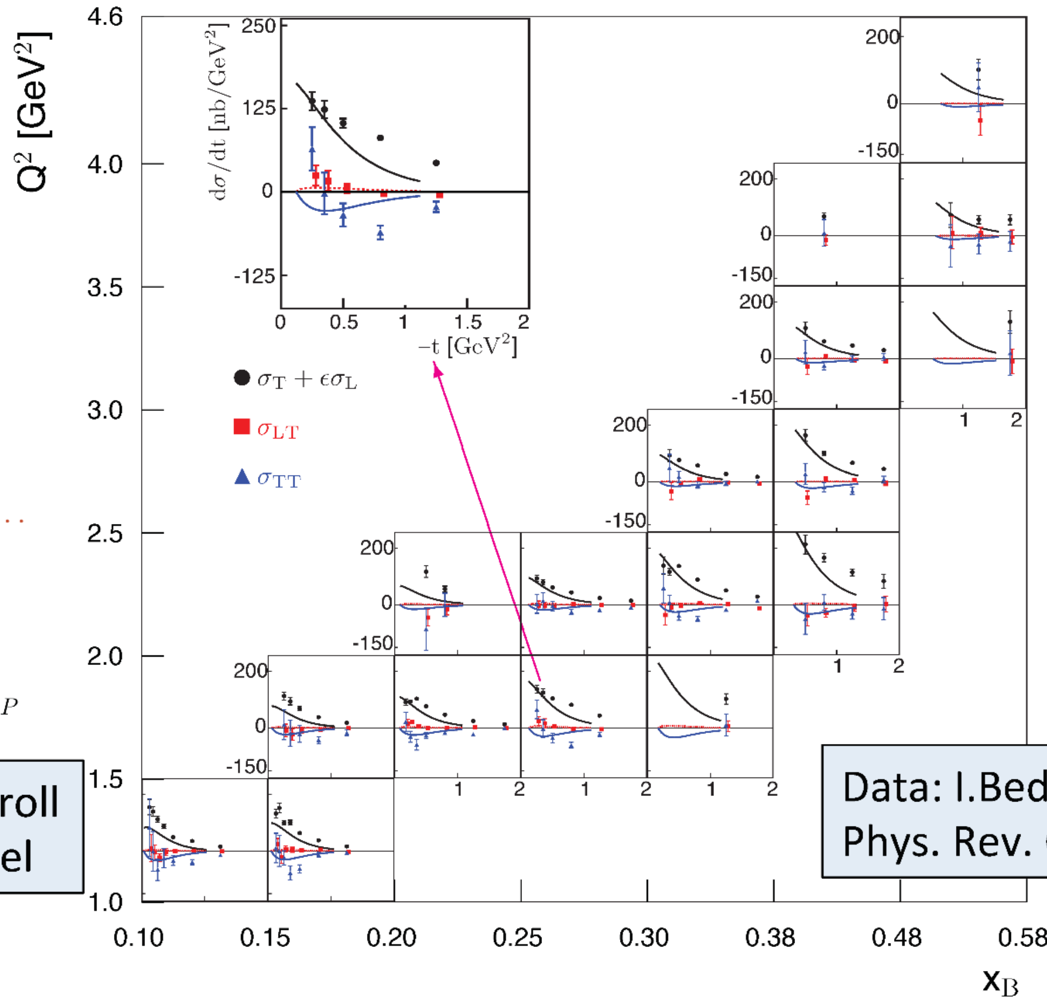
CLAS collaboration. I Bedlinskiy et al. Phys.Rev.Lett. 109 (2012) 112001

η Structure Functions

$(\sigma_T + \varepsilon\sigma_L)$ σ_{TT} σ_{LT}

$\gamma^* p \to p\eta$

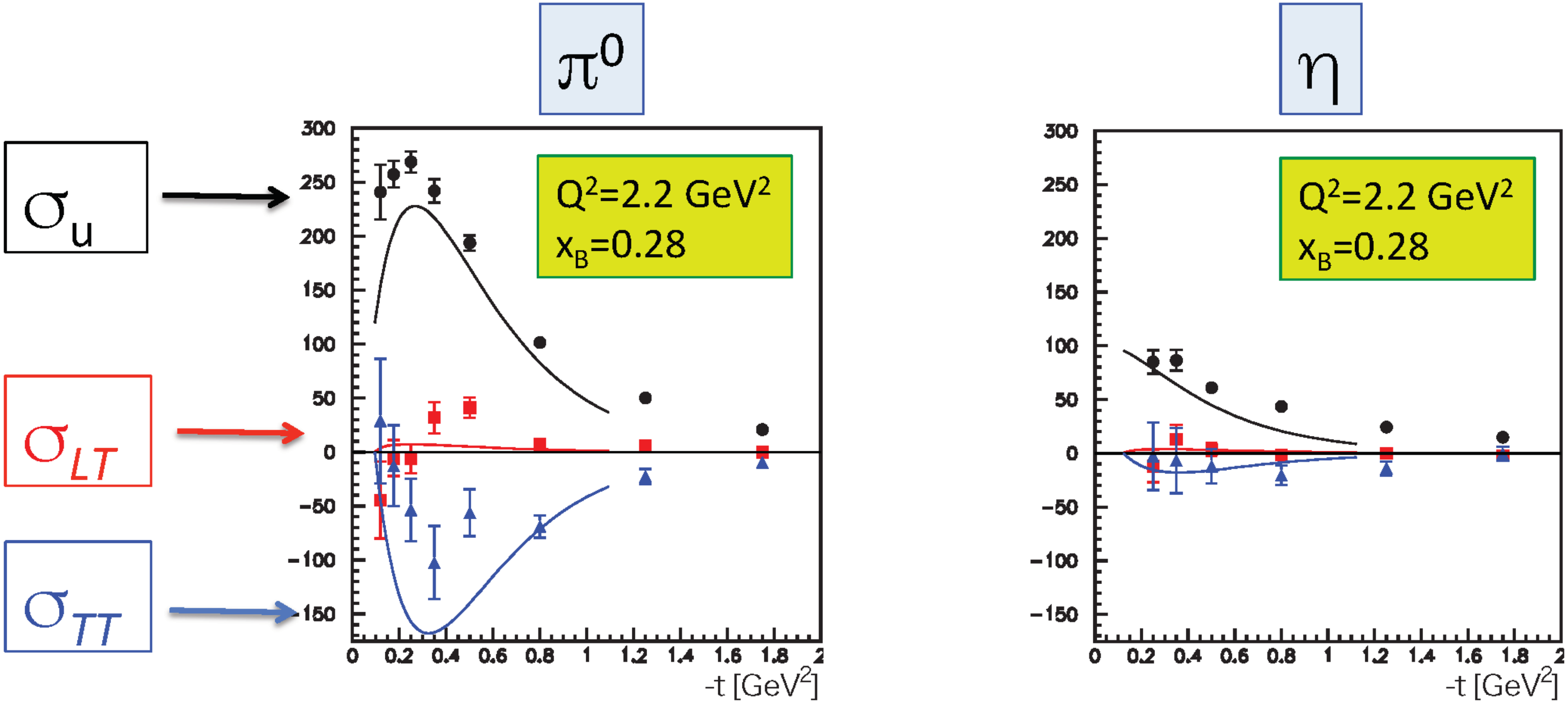




Curves: Goloskokov, Kroll
Transversity GPD model

Data: I.Bedlinskiy et al. (CLAS)
Phys. Rev. C **95**, 035202 (2017)

Comparison π^0/η



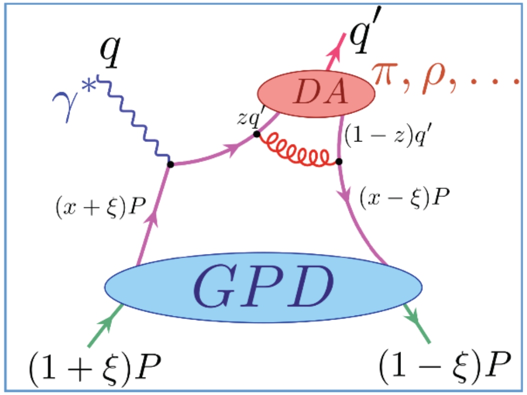
CLAS-Phys.Rev.C95(2017)

- $\sigma_U=\sigma_T+\varepsilon\sigma_L$ drops by a factor of 2.5 for η
- σ_{TT} drops by a factor of 10
- The GK GPD model (curves) follows the experimental data
- The statement about the ability of transversity GPD model to describe the pseudoscalar electroproduction becomes more solid with the inclusion of η data

Structure functions and 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

$$|\langle \bar{E}_T\rangle^{\pi,\eta}|^2 = \frac{k'}{4\pi\alpha}\frac{Q^8}{\mu_P^2}\frac{16m^2}{t'}\frac{d\sigma_{TT}^{\pi,\eta}}{dt}$$

$$|\langle H_T\rangle^{\pi,\eta}|^2 = \frac{2k'}{4\pi\alpha}\frac{Q^8}{\mu_P^2}\frac{1}{1-\xi^2}\left[\frac{d\sigma_T^{\pi,\eta}}{dt} + \frac{d\sigma_{TT}^{\pi,\eta}}{dt}\right]$$

$$\langle H_T\rangle = \Sigma_\lambda \int_{-1}^{1} dx M(x,\xi,Q^2,\lambda) H_T(x,\xi,t)$$

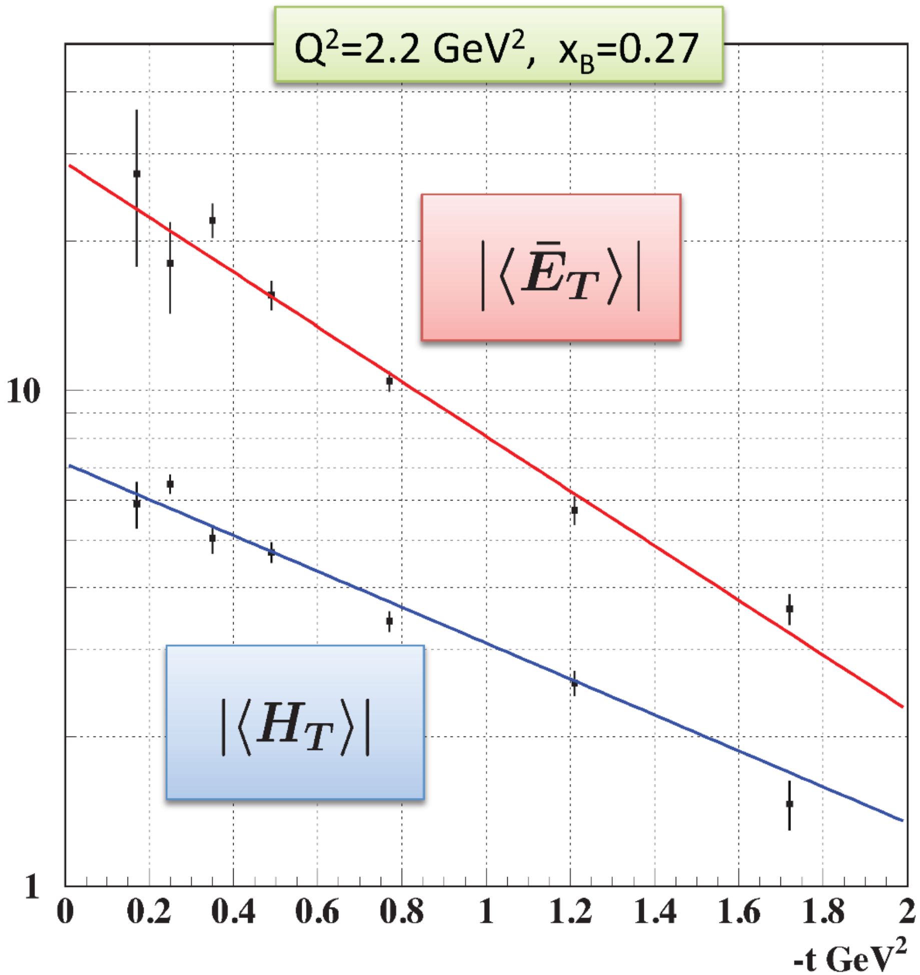
$$\langle \bar{E}_T\rangle = \Sigma_\lambda \int_{-1}^{1} dx M(x,\xi,Q^2,\lambda) \bar{E}_T(x,\xi,t)$$

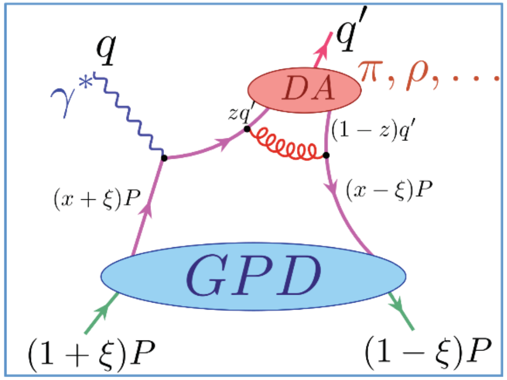
The brackets <F> denote the convolution of the elementary process with the GPD F (generalized form factors)

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

- We did not separate σ_T and σ_L
- However *in the approximation* of the transversity GPDs dominance, that is supported by Jlab data, $\sigma_L \ll \sigma_T$ we have direct access to the generalized form factors for π and η production.

π^0 Generalized Form Factors



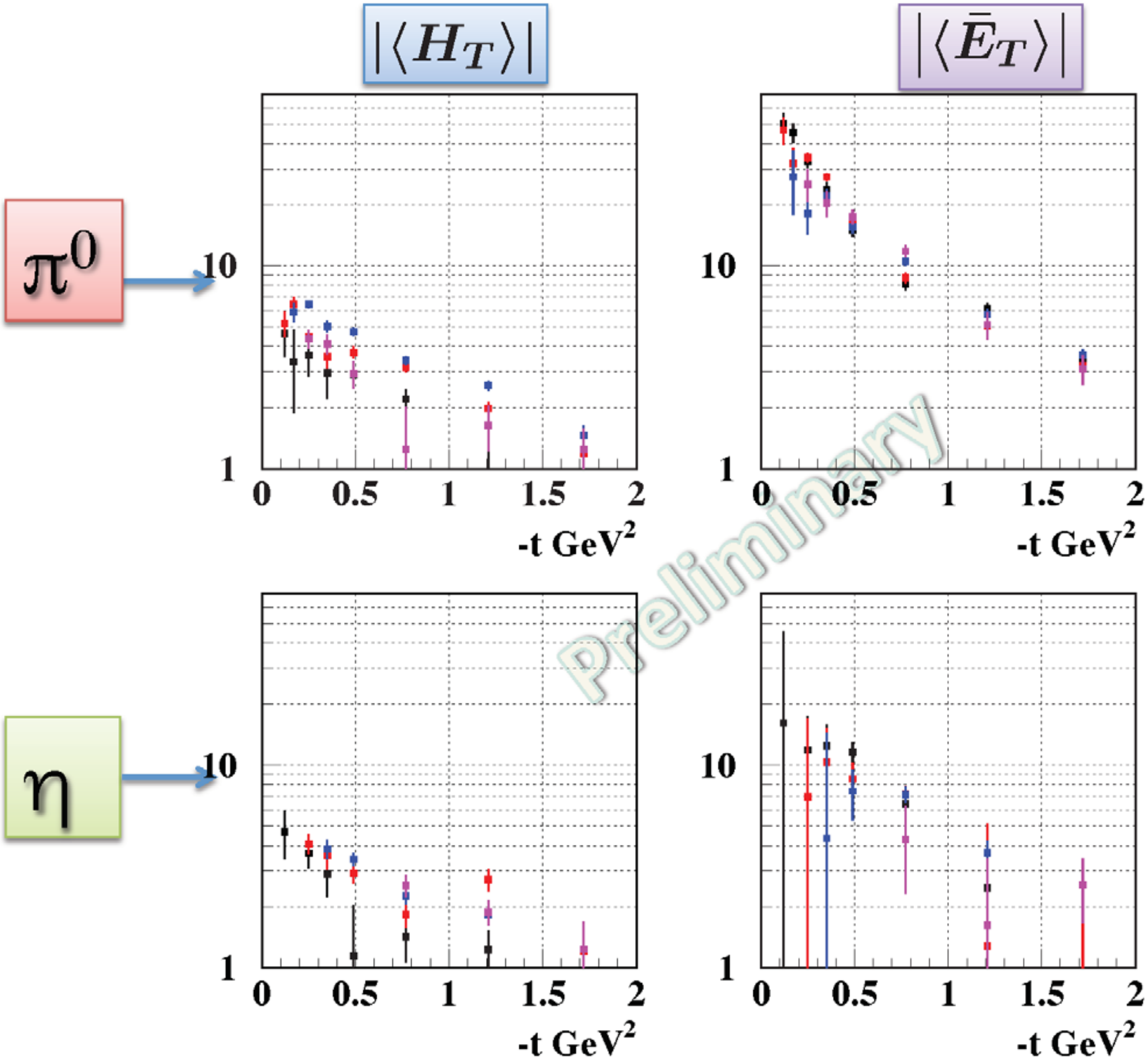


- $\bar{E}_T$ > H_T
- t-dependence is steeper for $\bar{E}_T$ than for H_T

- $|\langle E_T, H_T \rangle|$~exp(bt)
- b(E_T)=1.27 GeV^{-2}
- b(H_T)=0.98 GeV^{-2}

VK, arXiv:1601.04367

Generalized Form factors



Q^2 GeV^2	x_B
1.2	0.15
1.8	0.22
2.2	0.27
2.7	0.34

- $\bar{E}_T$ > H_T for π^0 and η
- t-dependence is steeper for $\bar{E}_T$ than for H_T
- Estimation of the systematic uncertainties connected with the used approximation is in progress

V. Kubarovsky (JLab)

GPD Flavor Decomposition

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

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

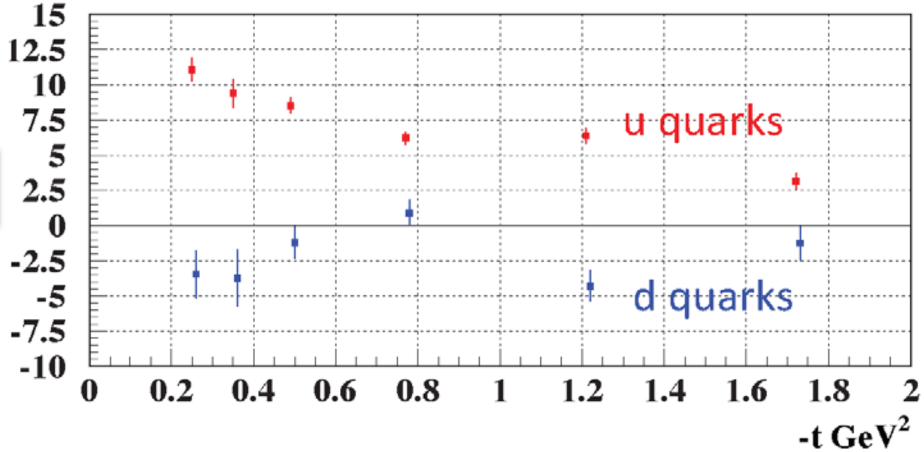
Similar expressions for $\bar{E}_T$

- GPDs appear in different flavor combinations for π^0 and η
- The combined π^0 and η data permit the flavor (u and d) decomposition for GPDs H_T and $\bar{E}_T$
- The u/d decomposition was done under simple assumption that the relative phase between u and d is 0 or 180 degrees.

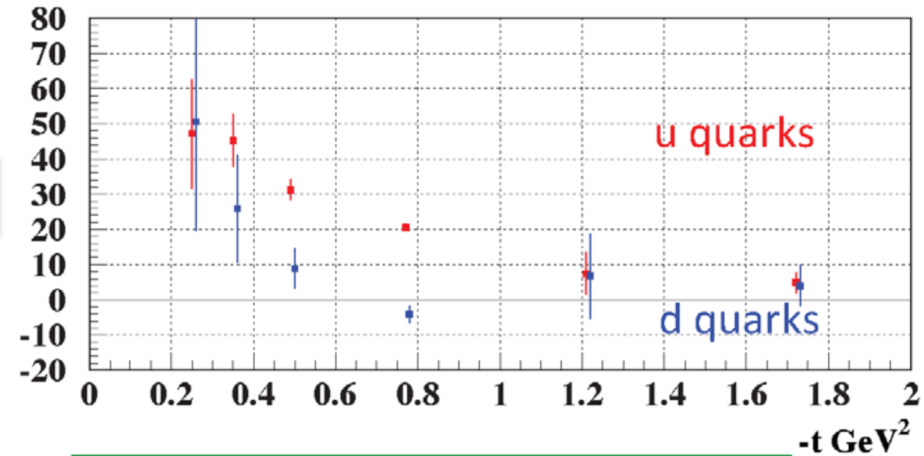
Flavor Decomposition of the Transversity GPDs

Q^2=1.8 GeV^2, x_B=0.22

$\langle H_T \rangle$



$\langle \bar{E}_T \rangle$



- $\langle H_T \rangle^u$ and $\langle H_T \rangle^d$ have different signs for u and d-quarks in accordance with the transversity function h_1 (Anselmino et al.)
- $|\langle \bar{E}_T \rangle|^d$ and $|\langle \bar{E}_T \rangle|^u$ seem to have the same signs

VK arXiv: 1601.04367 [hep-ex] 2016

V. Kubarovsky (Jlab)

Deeply Virtual Meson Production (DVMP)

$$\frac{2\pi}{\Gamma}\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}\cos 2\phi + \sqrt{\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi$$

unpolarized terms

longitudinally polarized beam

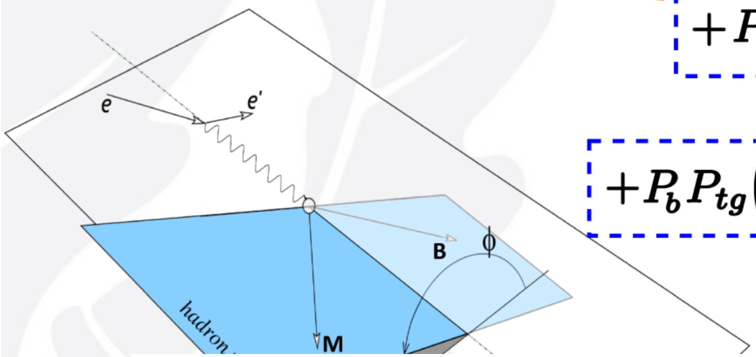
$$+P_b\sqrt{\epsilon(1-\epsilon)}\sigma_{LT'}\sin\phi$$

longitudinally polarized target

$$+P_{tg}\left(\sqrt{\epsilon(1+\epsilon)}\sigma_{UL}^{\sin\phi}\sin\phi + \epsilon\sigma_{UL}^{\sin 2\phi}\sin 2\phi\right)$$

$$+P_b P_{tg}\left(\sqrt{1-\epsilon^2}\sigma_{LL} + \sqrt{\epsilon(1-\epsilon)}\sigma_{LL}^{\cos\phi}\cos\phi\right)$$

longitudinally polarized beam
and
longitudinally polarized target



$$A_{LU}^{\sin\phi}\sigma_0 \sim \mathrm{Im}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

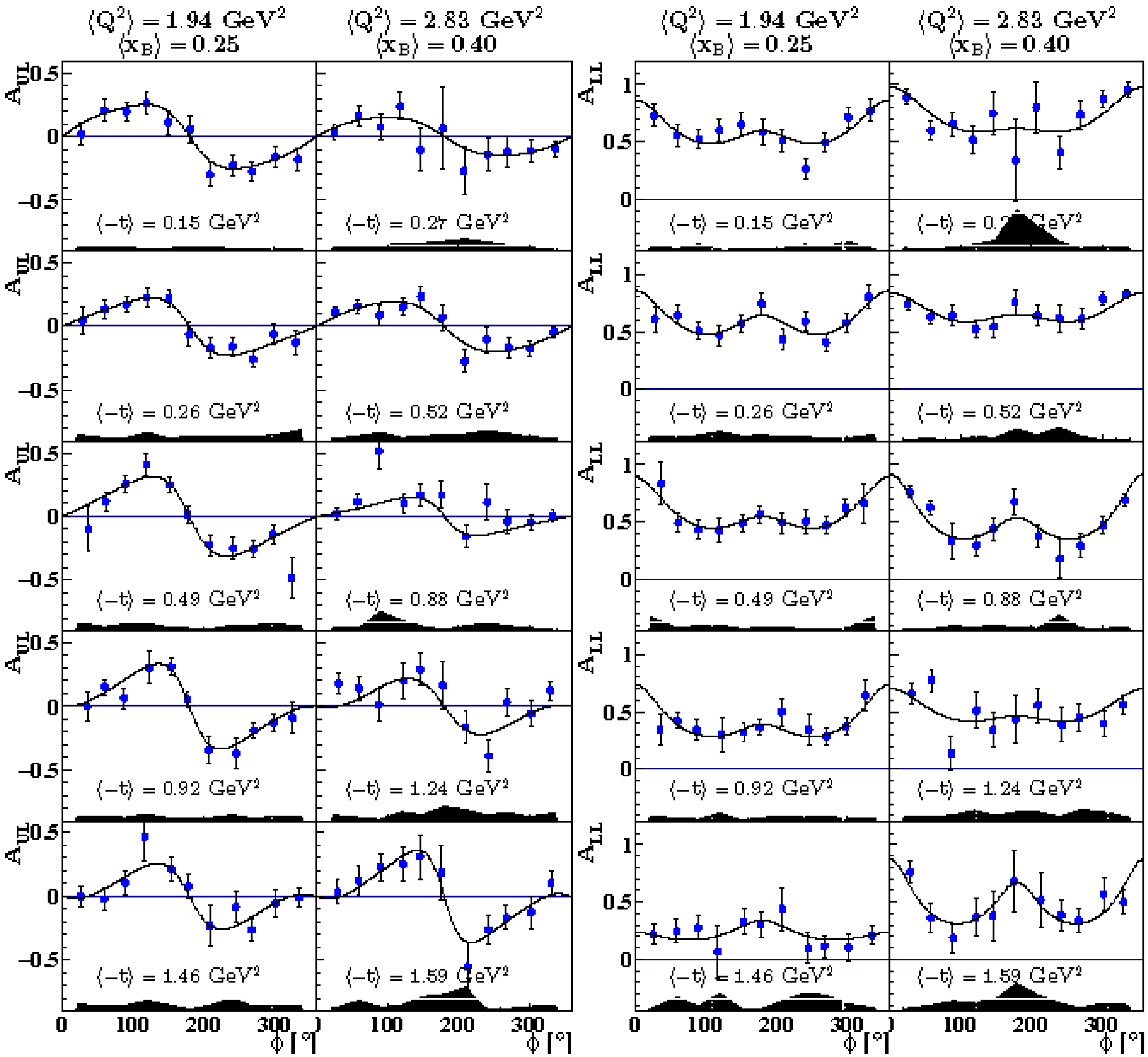
$$A_{UL}^{\sin\phi}\sigma_0 \sim \mathrm{Im}\left[\langle\bar{E}_T\rangle^*\langle\tilde{H}\rangle + \xi\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

$$A_{LL}^{\cos 0\phi}\sigma_0 \sim |\langle H_T\rangle|^2$$

$$A_{LL}^{\cos\phi}\sigma_0 \sim \mathrm{Re}\left[\langle\bar{E}_T\rangle^*\langle\tilde{H}\rangle + \xi\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

DVπ^0P Target and Double Spin Asymmetries ($A_{UL,}$ A_{LL})

A_{UL}



A_{LL}

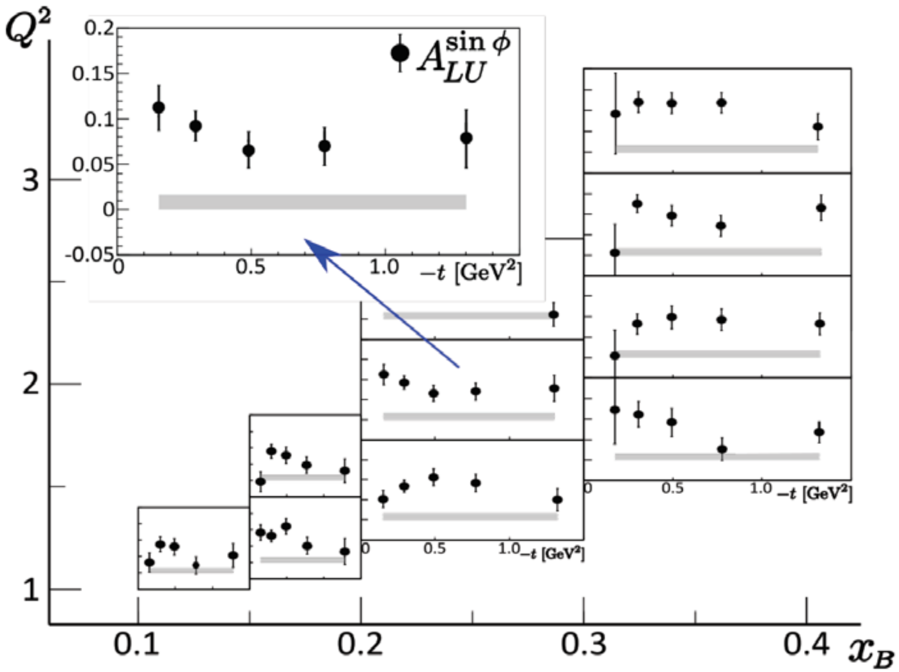
A. Kim (UConn)

$ep \rightarrow ep\pi^0$

beam, target and double spin asymmetries

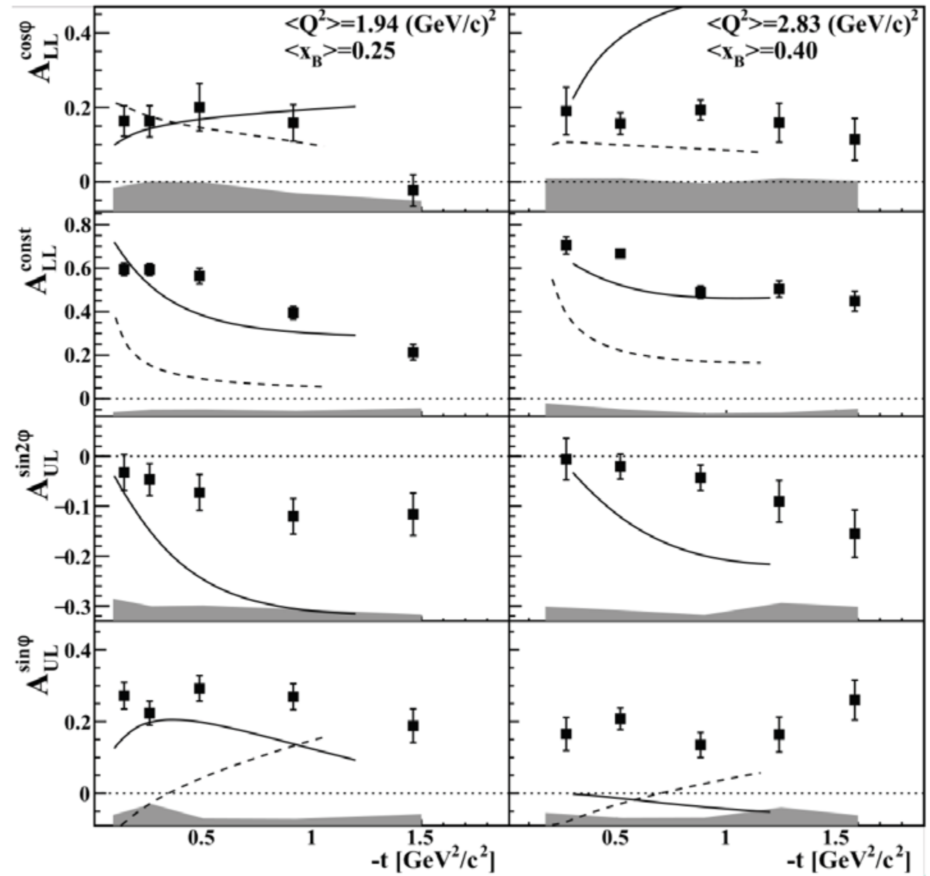
Beam spin asymmetries

R. De Masi *et al.* (CLAS collaboration) PRC**77**: 042201 (2008)



Target and double spin asymmetries

A. Kim *et al.* (CLAS collaboration) PLB**768**, 168 (2016)



Polarized observables:

$$A_{LU}^{\sin\phi}\sigma_0 \sim \mathrm{Im}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

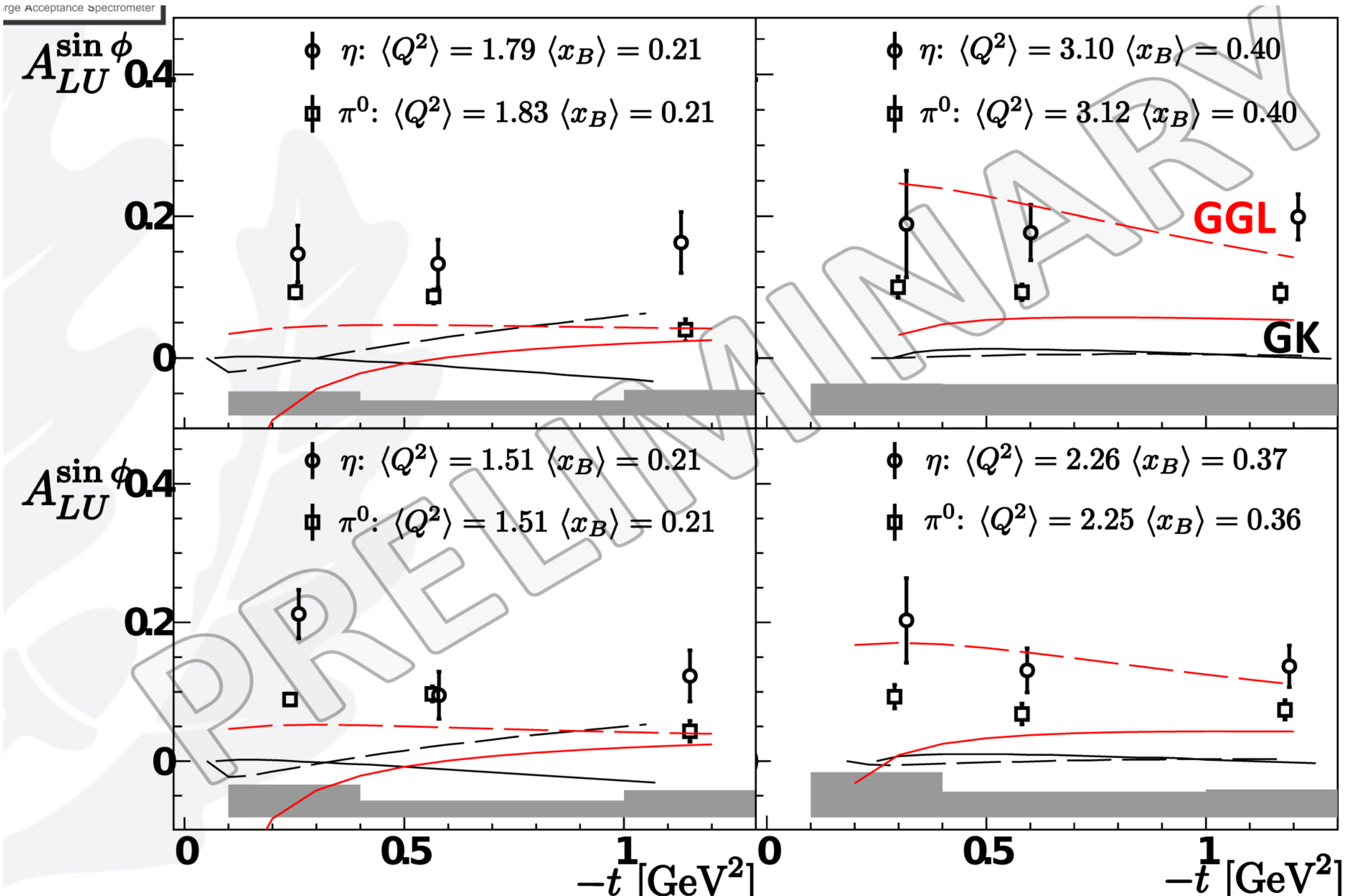
$$A_{UL}^{\sin\phi}\sigma_0 \sim \mathrm{Im}\left[\langle\bar{E}_T\rangle^*\langle\tilde{H}\rangle + \xi\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

$$A_{LL}^{\cos 0\phi}\sigma_0 \sim |\langle H_T\rangle|^2$$

$$A_{LL}^{\cos\phi}\sigma_0 \sim \mathrm{Re}\left[\langle\bar{E}_T\rangle^*\langle\tilde{H}\rangle + \xi\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

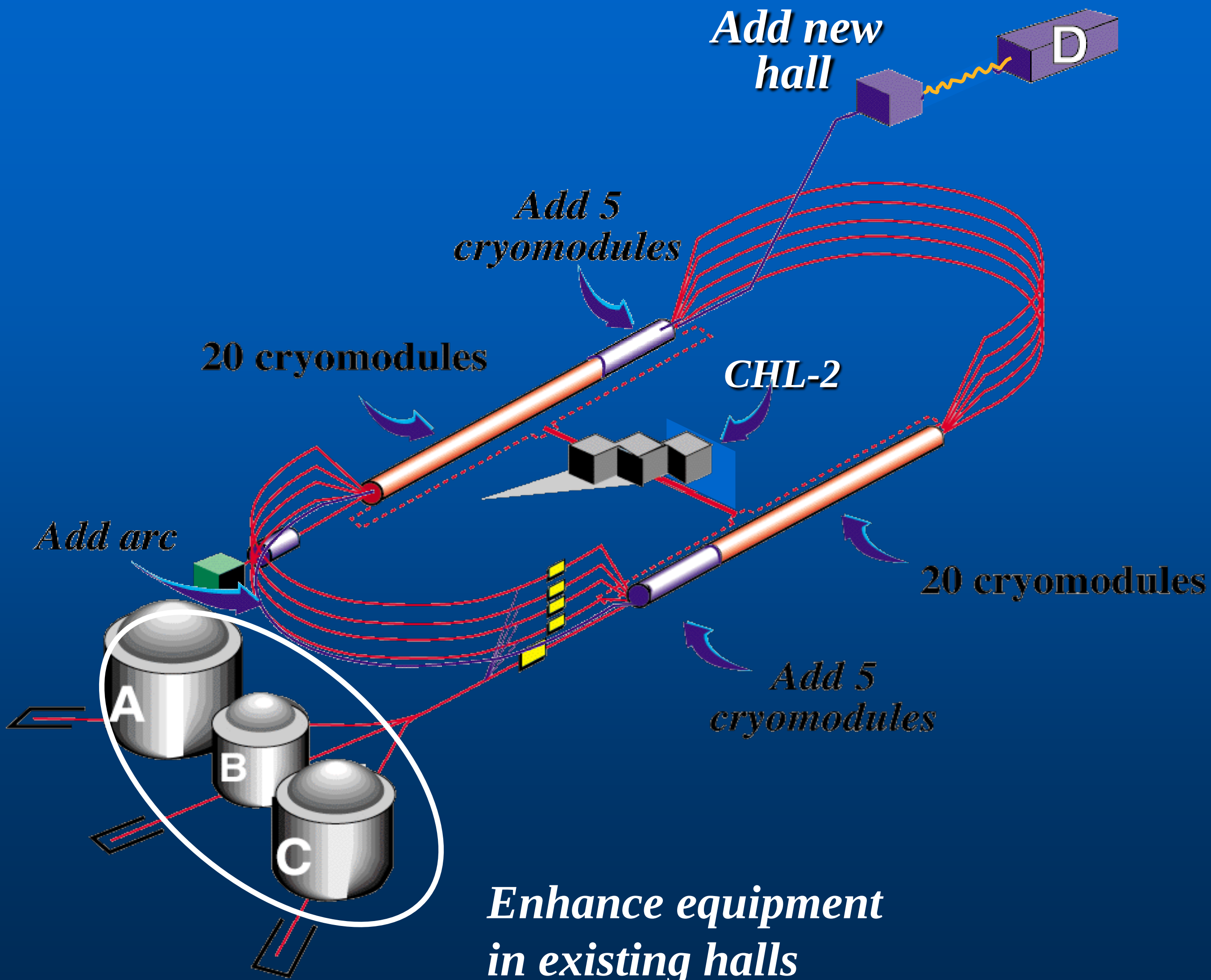
Dominated by transverse virtual photons contribution

Beam spin asymmetries: $\vec{e}p \rightarrow e'p'\eta$ and $\vec{e}p \rightarrow e'p'\pi^0$



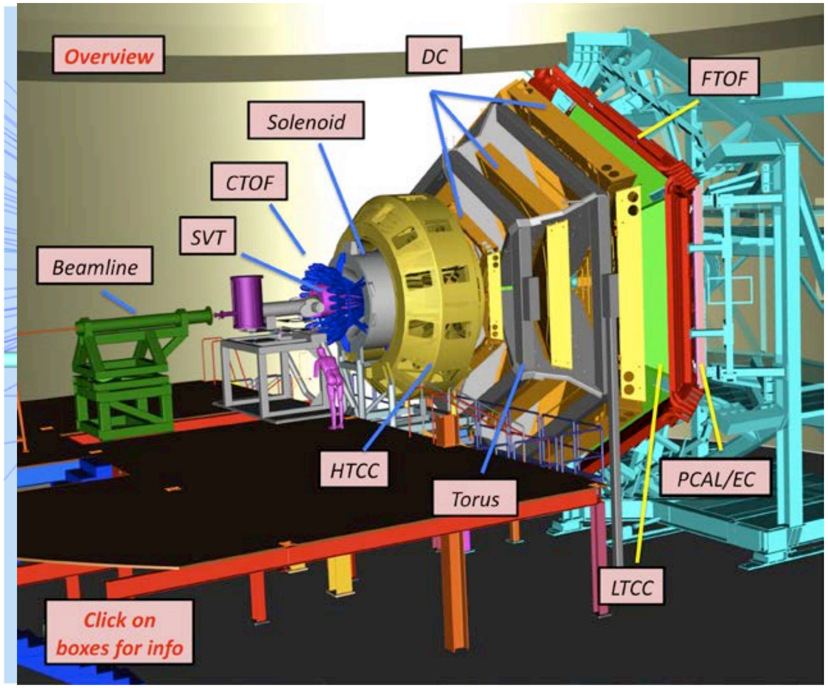
A. Kim (UConn)

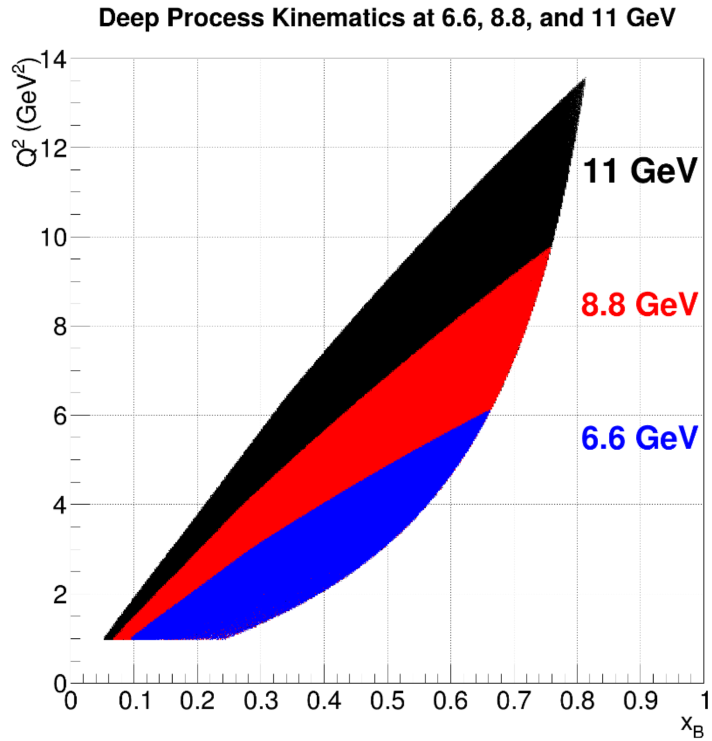
JLab Upgrade to 12 GeV



Enhance equipment in existing halls

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

http://www.jlab.org/Hall-B/clas12-web/

CLAS12 GPD Program

Number	Title	Contact	Days	Energy	Target
E12-06-108	Hard Exclusive Electroproduction of π^0 and η	Stoler	80	11	lH_2
E12-06-119	Deeply Virtual Compton Scattering	Sabatie	80	11	lH_2
E12-12-001	Timelike Compton Scat. & J/Ψ prod. in e^+e^-	Nadel-Turonski	120	11	lH_2
E12-12-007	Exclusive ϕ meson electroproduction	Stoler	60	11	lH_2
E12-11-003	DVCS on Neutron Target	Niccolai	90	11	lD_2
E12-06-119	Deeply Virtual Compton Scattering	Sabatie	120	11	NH_3
C12-12-010	DVCS with a transverse target	Elouadrhiri	110	11	HD-ice
E12-16-010	DVCS with CLAS12 at 6.6 GeV and 8.8 GeV	Elouadrhiri	50+50	6.6 & 8.8	lH_2

Summary

- Large data sets (cross sections, single and double spin asymmetries) in a wide kinematic region are available from 6 GeV.
- Large number of experimental observables provide better constraints for parameterizations of underlying GPDs.
- DVMP combined with DVCS provides access to the chiral-even and chiral-odd GPDs.
- Extensive GPD program with CLAS12 at JLab is about to start, and will produce new exciting results.

η / π^0 Ratio

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

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

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

Chiral-odd GPD models predict this ratio to be ~1/3 at CLAS kinematics

Chiral-even GPD models predict this ratio to be around 1