



Deeply Virtual Meson Production at Jefferson Lab

Valery Kubarovsky

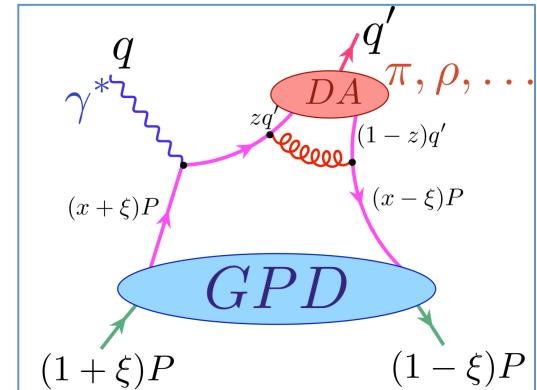
Jefferson Lab



The 21st International Symposium on Spin Physics
October 20-24, 2014, Beijing, China

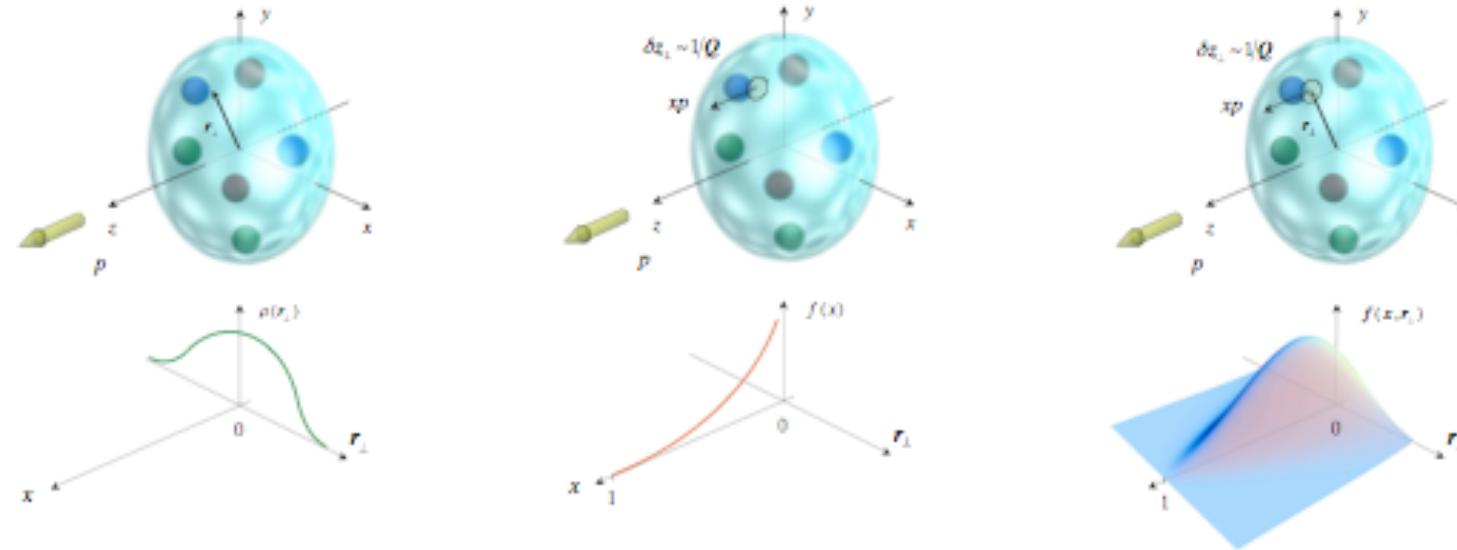
Outline

- Physics motivation
- CLAS data on pseudoscalar meson electroproduction
- Transversity GPD and structure functions
- Flavor decomposition of the Transversity GPDs
- Conclusion



Description of hadron structure in terms of GPDs

D. Müller ′, X. Ji, A. Radyushkin



Nucleon form factors

transverse charge &
current densities

Nobel prize 1961- R. Hofstadter

Structure functions

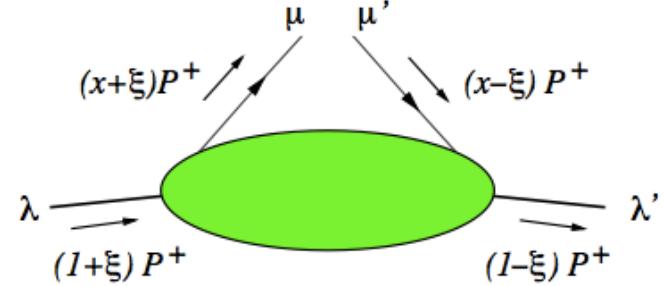
quark longitudinal
momentum (polarized and
unpolarized) distributions

Nobel prize 1990 – J.Friedman,
H. Kendall, R. Taylor

GPDs

correlated quark momentum
distributions (polarized and
unpolarized) in transverse
space

Generalized Parton Distributions



- GPDs are the functions of three kinematic variables: x , ξ and t
- There are 4 chiral even GPDs where partons do not flip helicity $H, \tilde{H}, E, \tilde{E}$
- 4 chiral odd GPDs flip the parton helicity $H_T, \tilde{H}_T, E_T, \tilde{E}_T$
- The chiral-odd GPDs are difficult to access since subprocesses with quark helicity-flip are suppressed

Chiral-odd GPDs

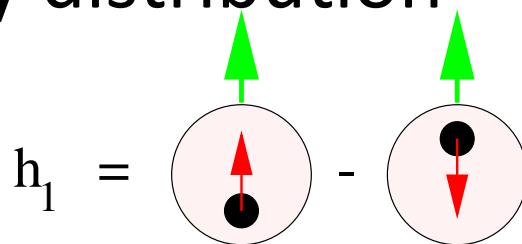
- Very little known about the chiral-odd GPDs
- Anomalous tensor magnetic moment

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

- (Compare with anomalous magnetic moment)

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

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



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

$$ep \rightarrow ep\pi^0$$

Structure functions and GPDs

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

Leading twist σ_L

$$\sigma_L = \frac{4\pi\alpha_e}{\kappa Q^2} [(1 - \xi^2) |\langle \tilde{H} \rangle|^2 - 2\xi^2 \text{Re}(\langle \tilde{H} \rangle \langle \tilde{E} \rangle) - \frac{t}{4m^2} \xi^2 |\langle \tilde{E} \rangle|^2]$$

σ_L suppressed by a factor coming from:

$$\tilde{H}^\pi = \frac{1}{3\sqrt{2}} [2\tilde{H}^u + \tilde{H}^d]$$

\tilde{H}^u and \tilde{H}^d have opposite signs

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

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

The brackets $\langle F \rangle$ denote the convolution of the elementary process with the GPD F (generalized form factors)

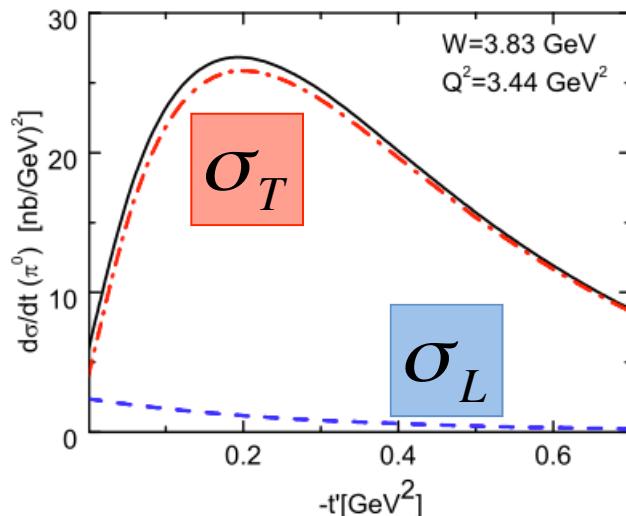
S. Goloskokov and P. Kroll
 S. Liuti and G. Goldstein

Structure functions and GPDs

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

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

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



Transversity GPD model

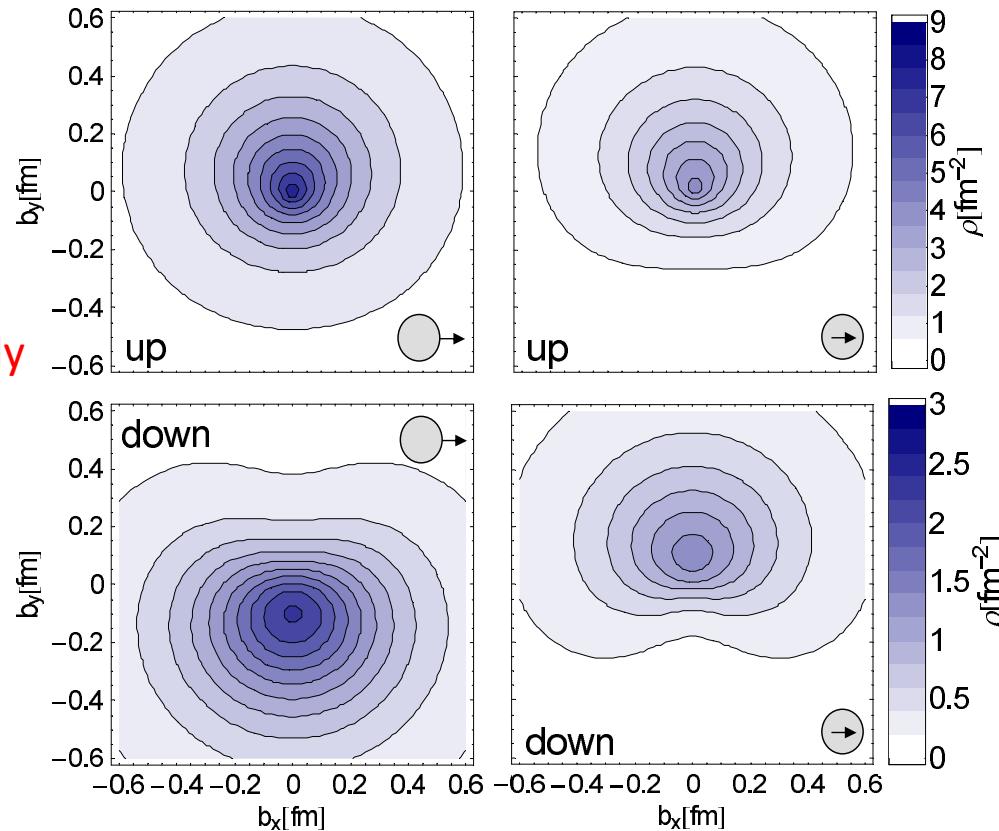
S. Goloskokov and P. Kroll

S. Liuti and G. Goldstein

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

Transverse Densities for u and d Quarks in the Nucleon

Strong distortions
for unpolarized
quarks in transversely
polarized nucleon

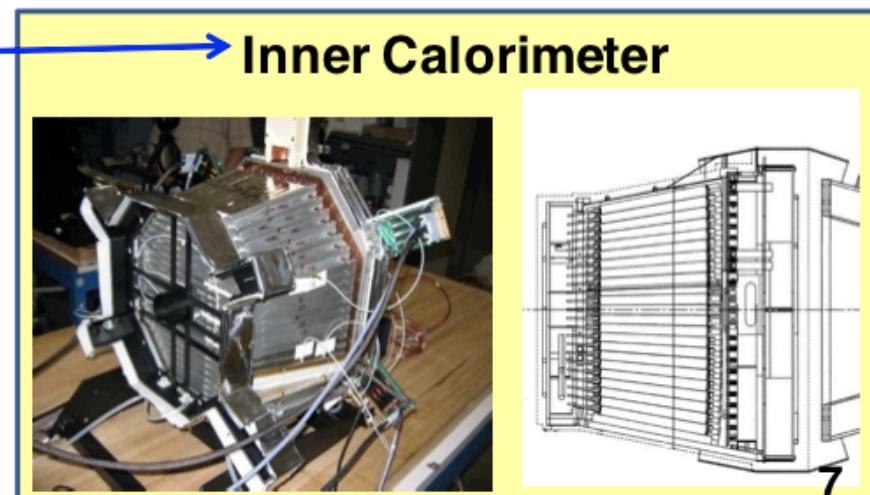
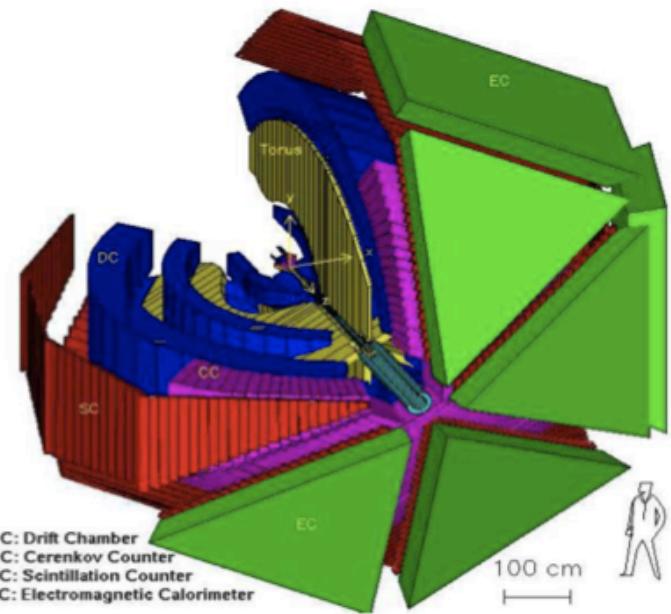
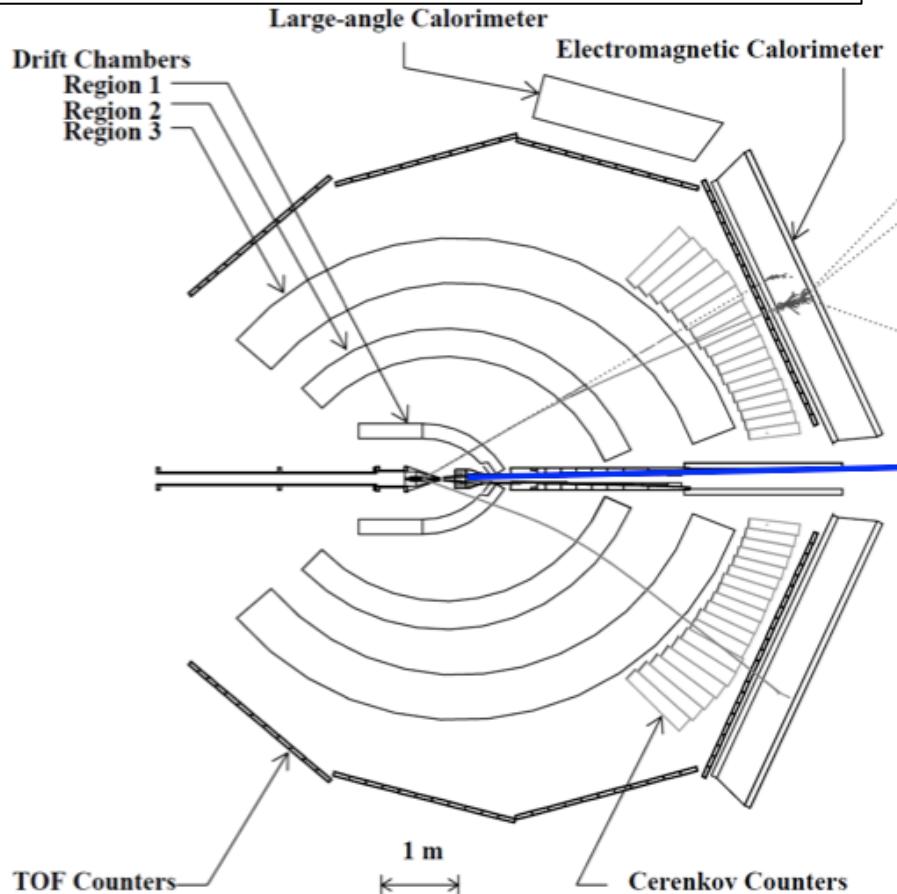


Strong distortions
for transversely
polarized quarks
in an unpolarized
nucleon

Described by E

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

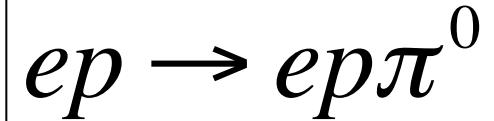
CEBAF Large Acceptance Spectrometer CLAS



CLAS Lead Tungstate Electromagnetic Calorimeter

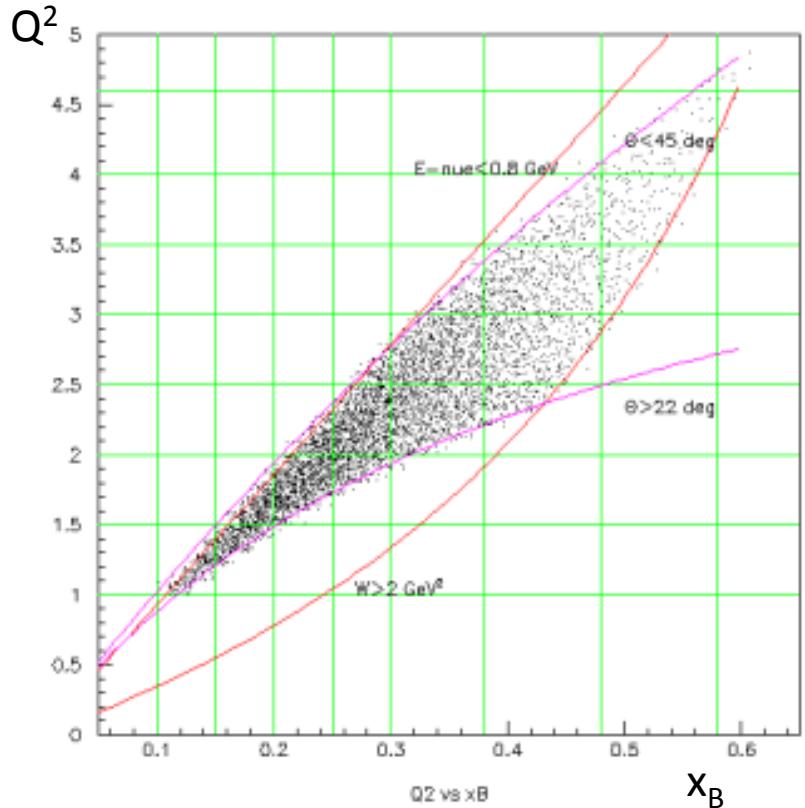
424 crystals, 18 RL,
Pointing geometry,
APD readout

4 Dimensional Grid



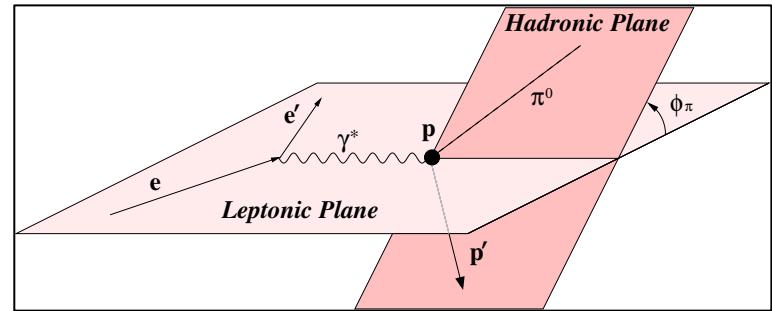
Rectangular bins are used.

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

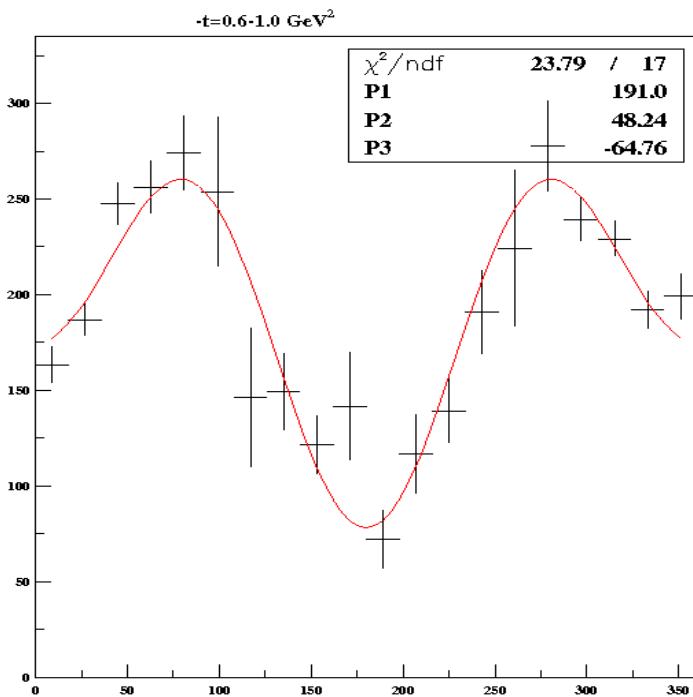


Structure Functions

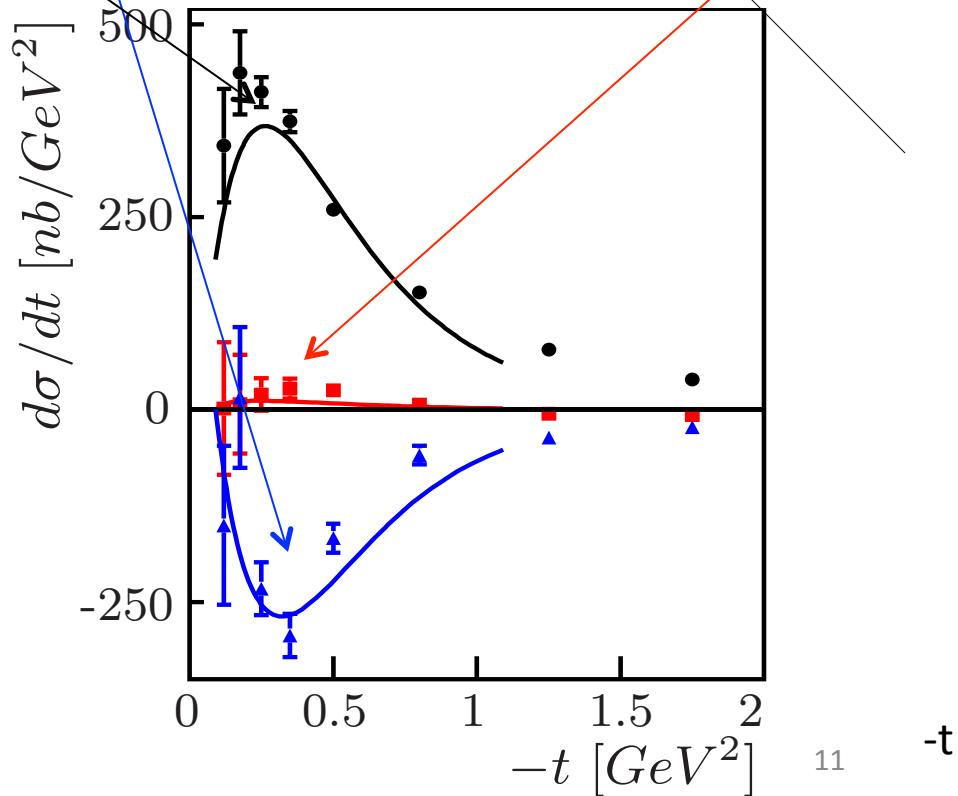
$$\sigma_U = \sigma_T + \varepsilon \sigma_L \quad \sigma_{TT} \quad \sigma_{LT}$$



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

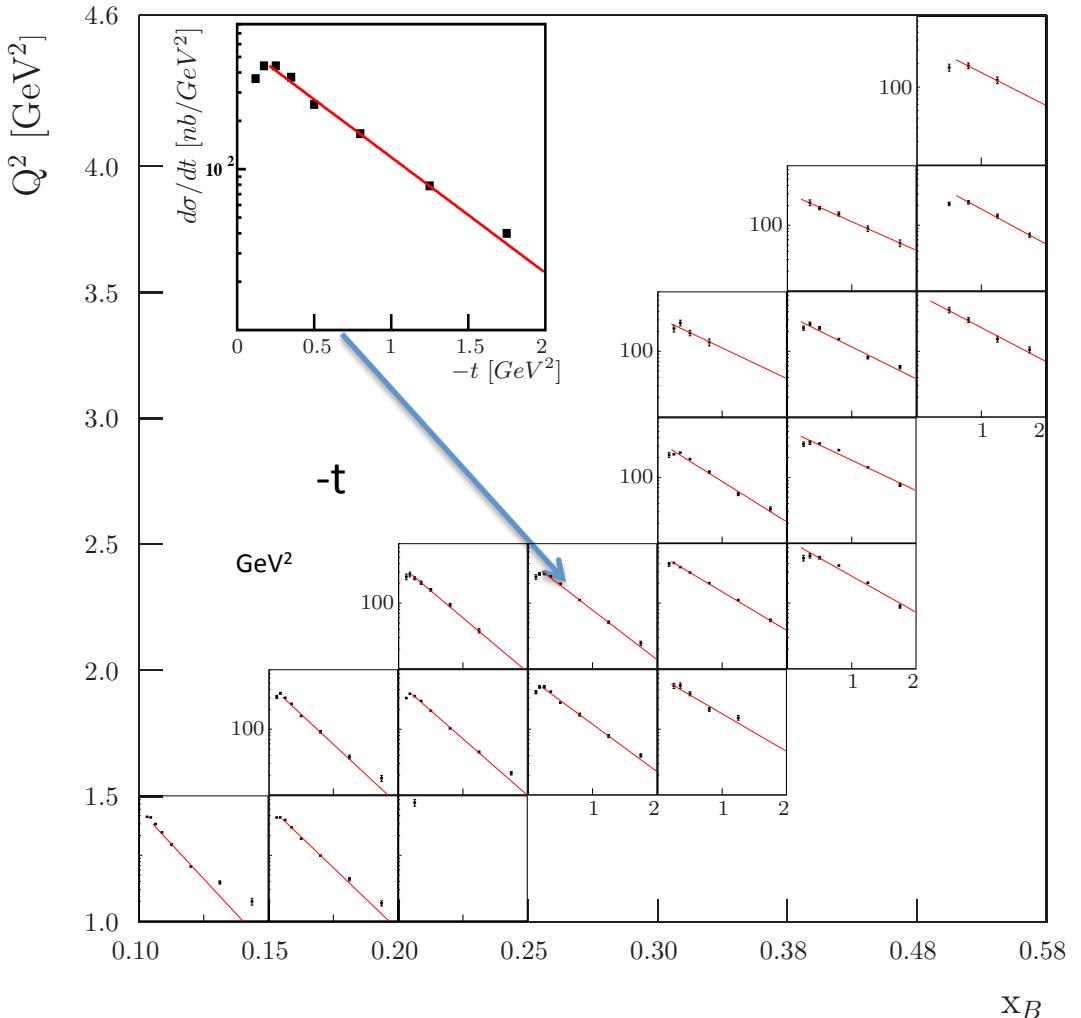
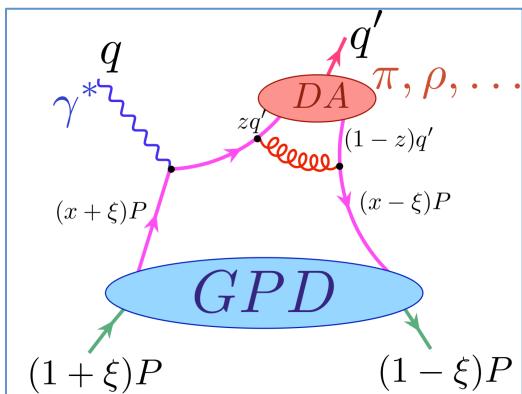


ϕ distribution



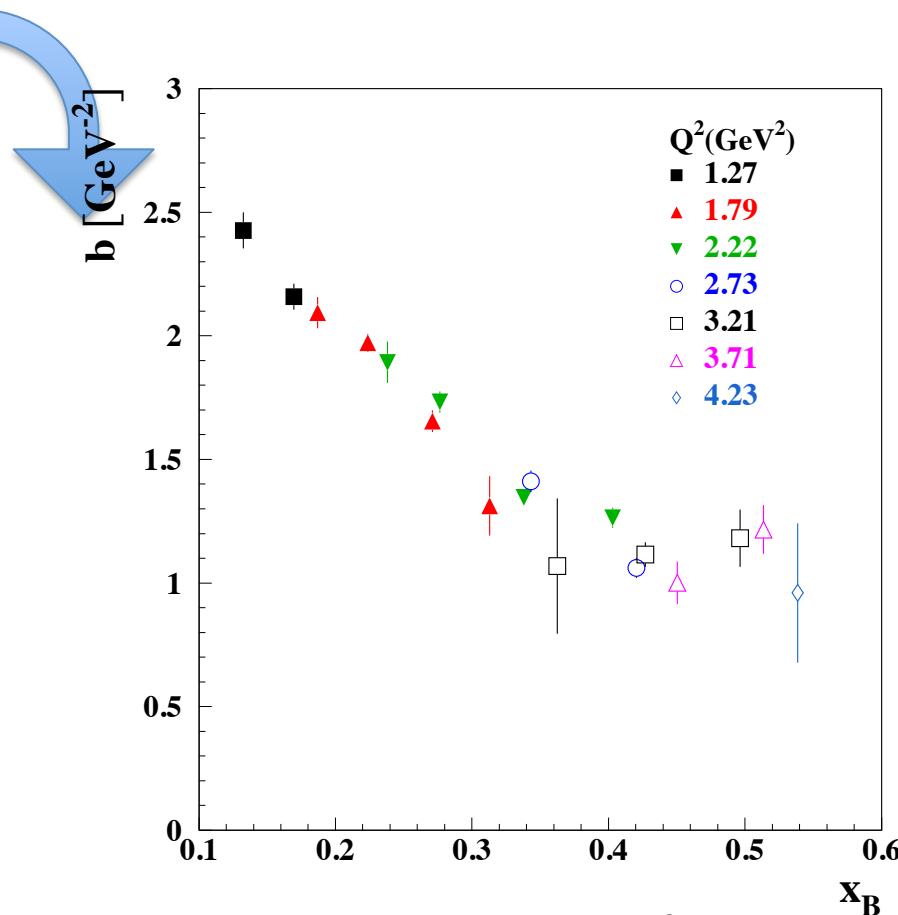
$$d\sigma_U/dt$$

$$\frac{d\sigma}{dt}(\gamma^* p \rightarrow e p \pi^0) \propto e^{bt}$$



t-slope parameter: x_B dependence

$$\frac{d\sigma}{dt} \propto e^{bt}$$

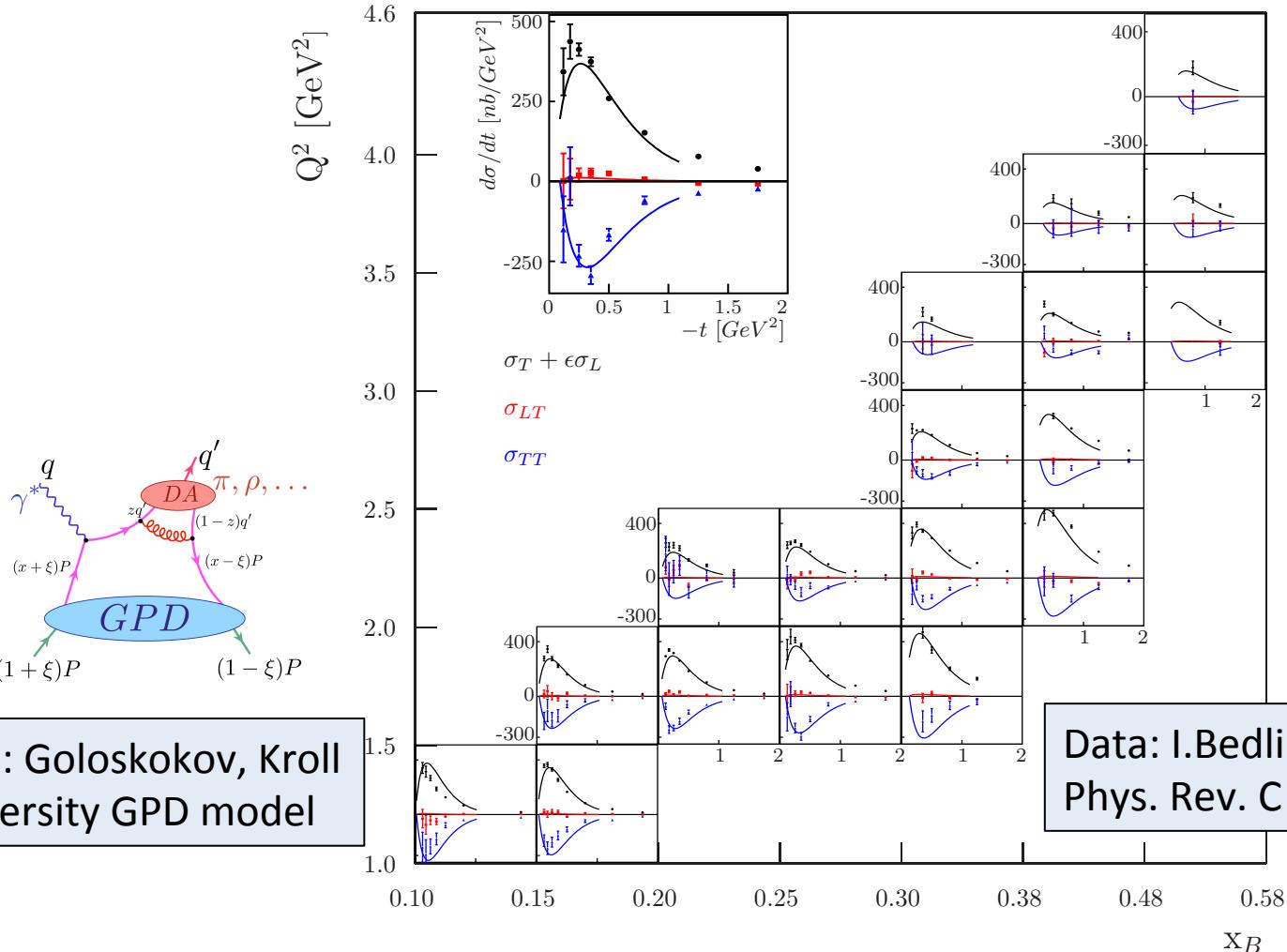


The slope parameter is decreasing with increasing x_B . The Q^2 dependence is weak. Looking to this picture we can say that the perp width of the partons with $x \rightarrow 1$ goes to zero.

Structure Functions

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

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



Curves: Goloskokov, Kroll
Transversity GPD model

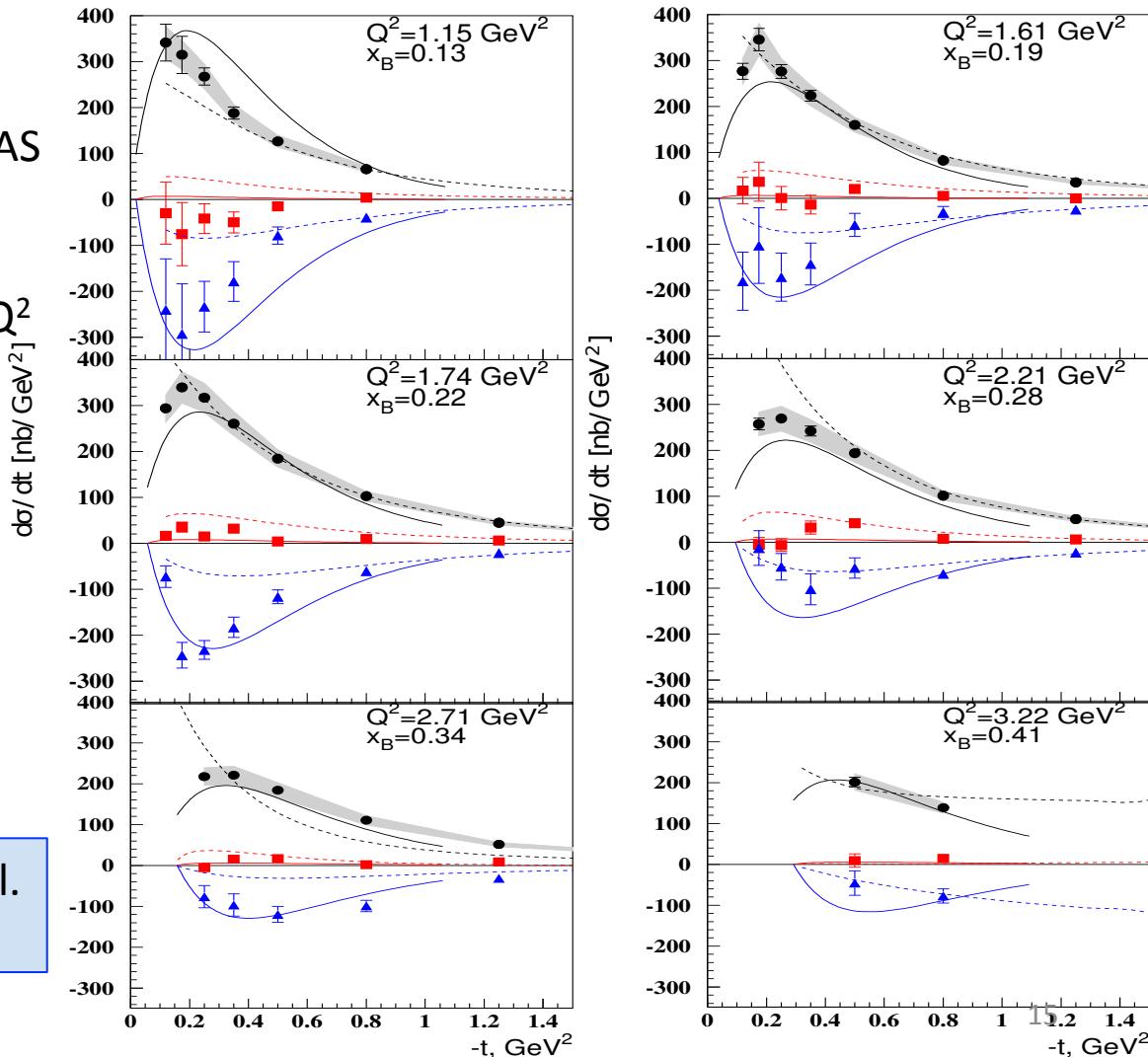
Data: I.Bedlinskiy et al. (CLAS)
Phys. Rev. C 90, 039901 (2014)

CLAS data and GPD theory predictions

Solid: S. Goloskokov and P. Kroll

Dots: S. Liuti and G. Goldstein

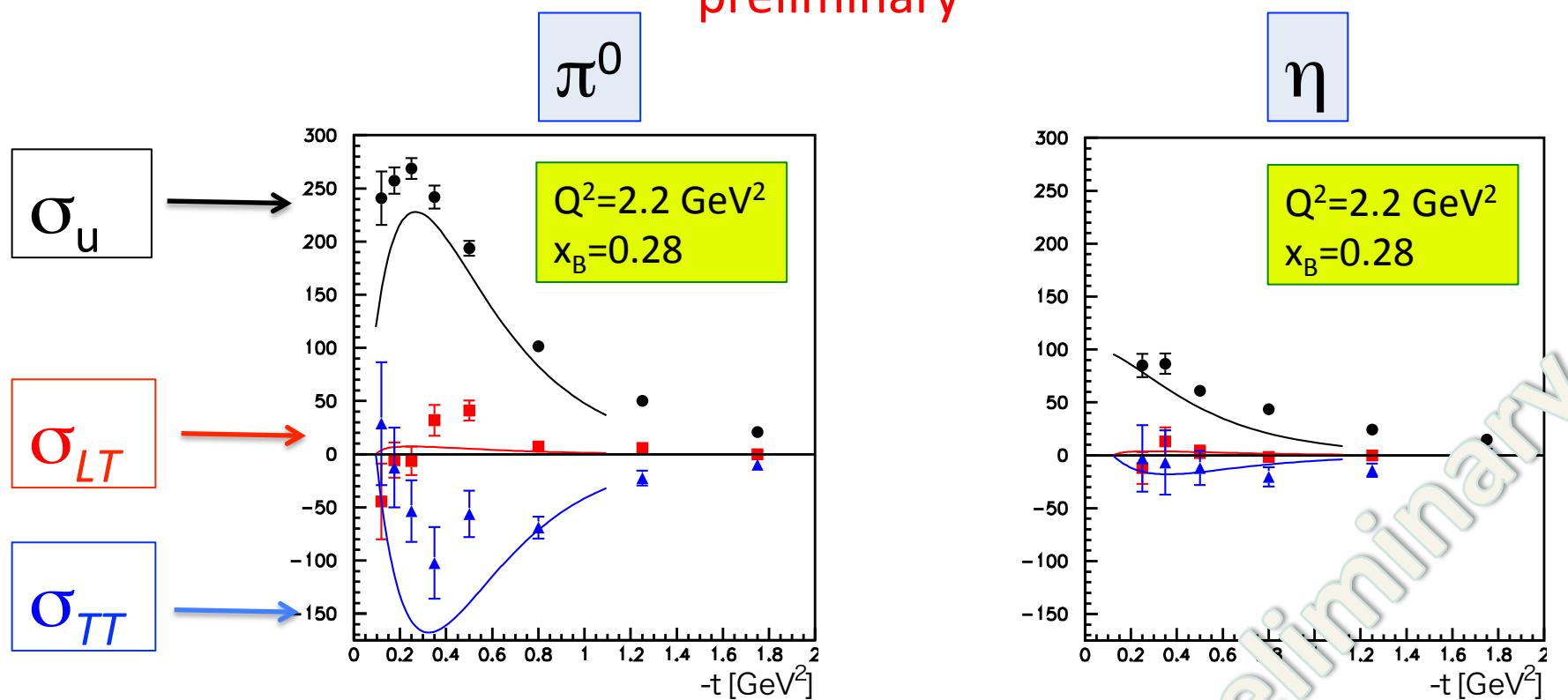
- **Transversity GPDs** H_T and $\bar{E}_T = 2\tilde{H}_T + E_T$ dominate in CLAS kinematics.
- The model was optimized for low x_B and high Q^2 . The corrections t/Q^2 were omitted
- The model successfully describes CLAS data even at low Q^2
- Pseudoscalar meson production provides unique possibility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



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

Comparison π^0/η

preliminary

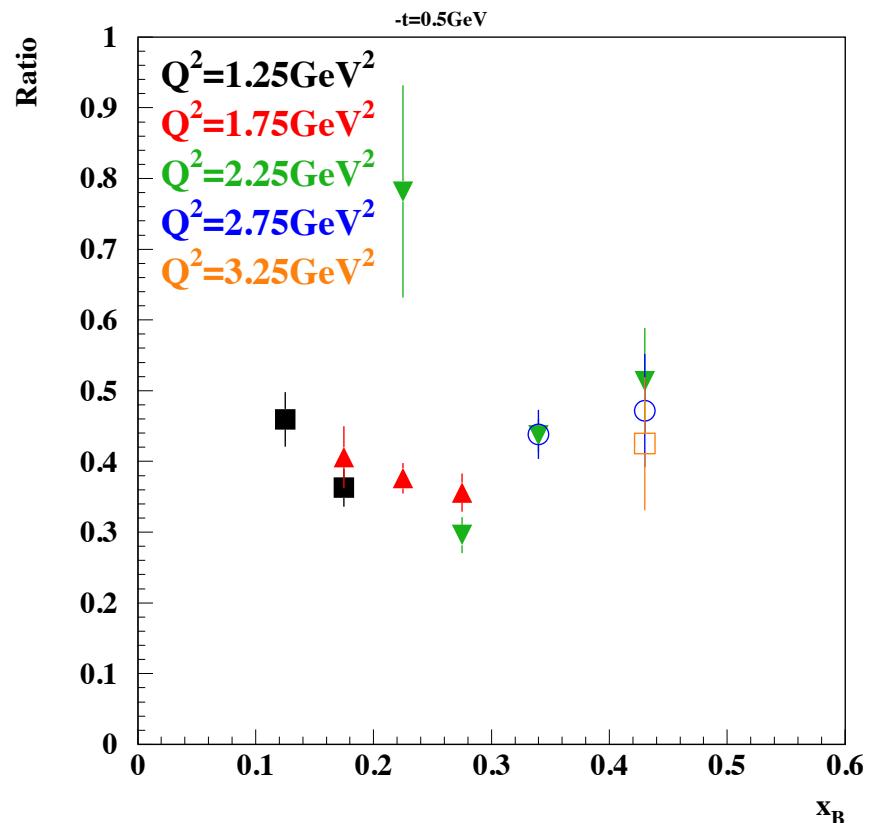


- $\sigma_u = \sigma_T + \varepsilon \sigma_L$ drops by a factor of 2.5 for η
- σ_{TT} drops by a factor of 10
- The GK GPD model (curves) follows the experimental data
- The statement about the transversity GPD dominance in the pseudoscalar electroproduction becomes more solid with the inclusion of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

η/π^0 ratio

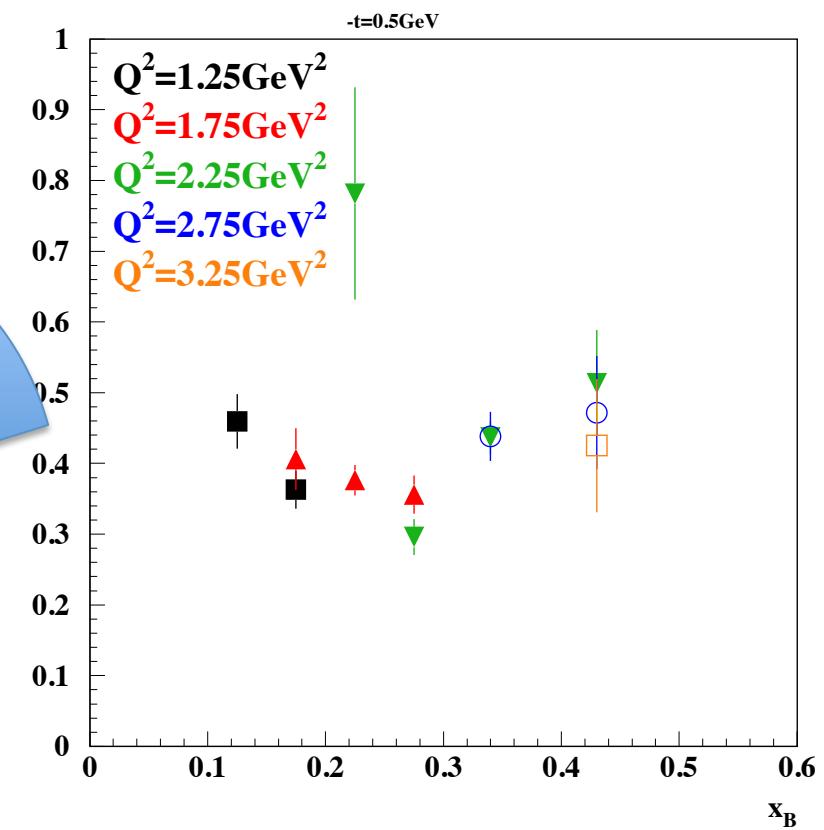
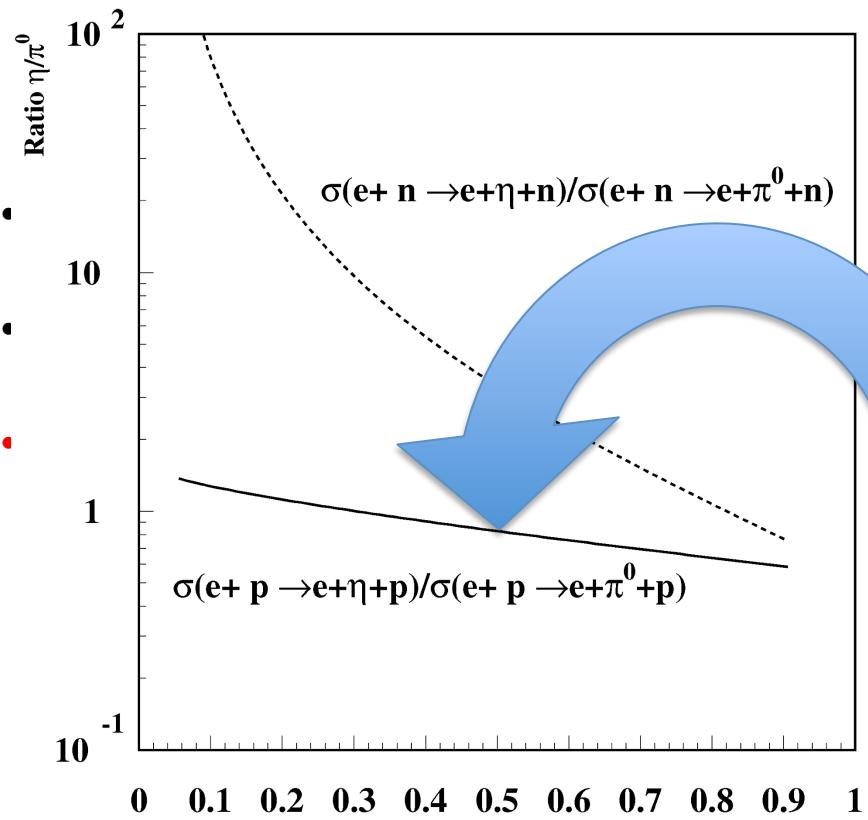
$$\frac{\sigma(ep \rightarrow ep\eta)}{\sigma(ep \rightarrow ep\pi^0)}$$

- The dependence on x_B and Q^2 is very weak.
- Chiral odd GPD models predict this ratio to be $\sim 1/3$ at CLAS kinematics
- Chiral even GPD models predict this ratio to be around 1 (at low $-t$).



η/π^0 ratio

$$\frac{\sigma(ep \rightarrow ep\eta)}{\sigma(ep \rightarrow ep\pi^0)}$$



Theoretical prediction R=1 for the
Chiral-even GPD models ($\sigma_L \gg \sigma_T$)

Structure functions and GPDs

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

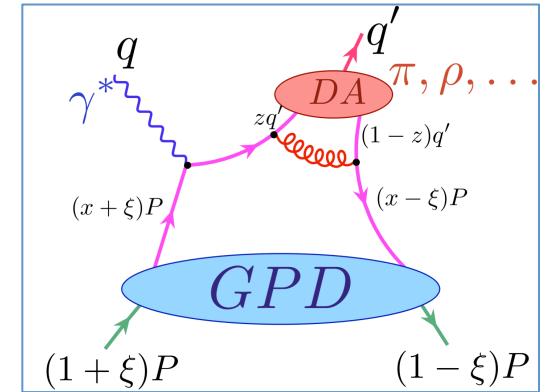
$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'} \frac{\mu_P^2}{Q^8} \frac{t'}{16m^2} |\langle \bar{E}_T \rangle|^2$$

Goloskokov, Kroll
Transversity GPD model



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

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



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

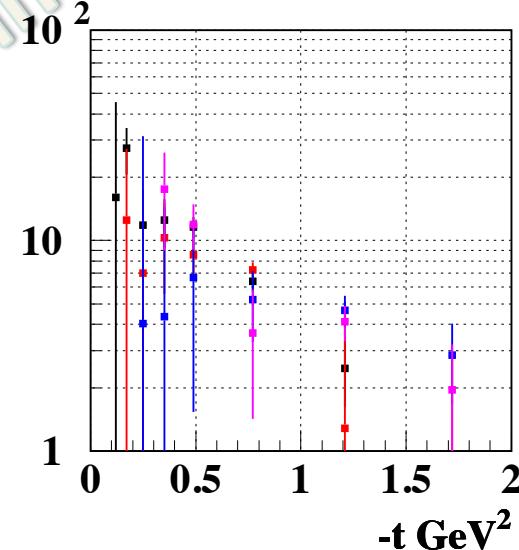
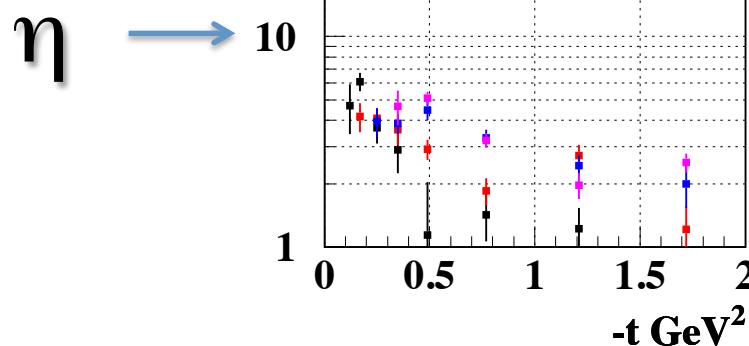
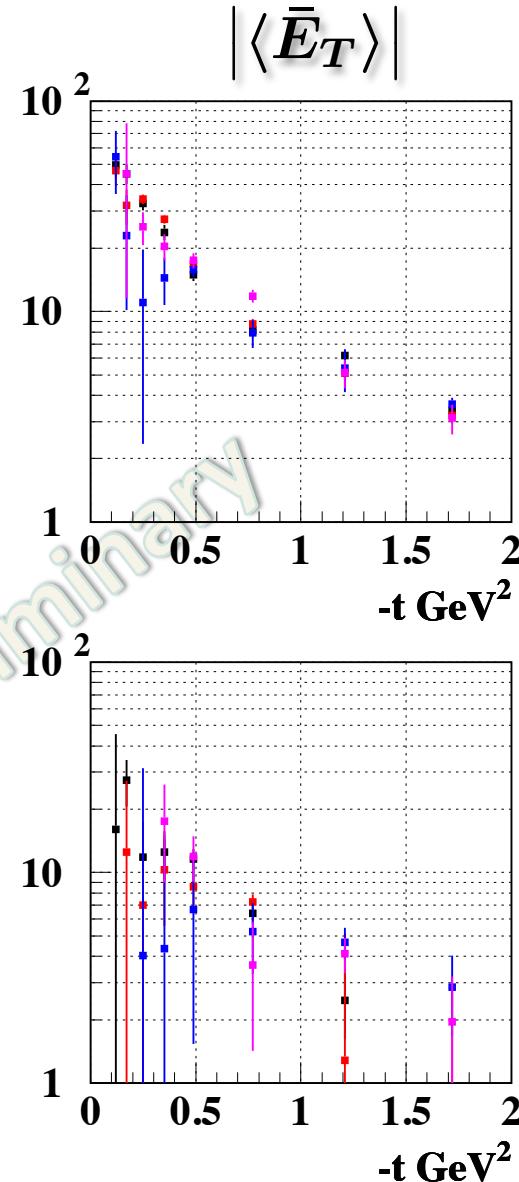
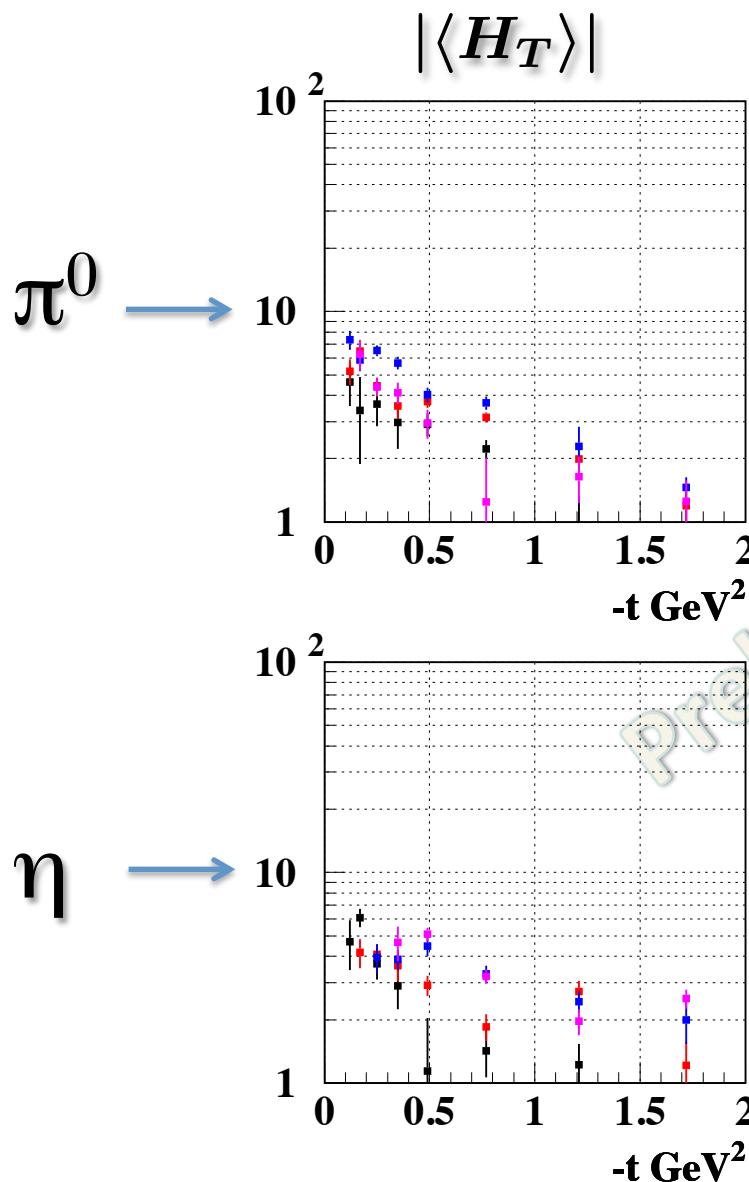
$$\langle \bar{E}_T \rangle = \Sigma_\lambda \int_{-1}^1 dx M(x, \xi, Q^2, \lambda) \bar{E}_T(x, \xi, t)$$

The brackets $\langle F \rangle$ denote the convolution of the elementary process with the GPD F
(generalized form factors)

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

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

Generalized Form factors



$Q^2 \text{ GeV}^2$	x_B
1.2	0.15
1.8	0.22
2.2	0.27
2.7	0.34

- $\bar{E}_T \gg H_T$ for π^0 and η
- t-dependence is steeper for \bar{E}_T than for H_T

GPD Flavor Decomposition

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

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



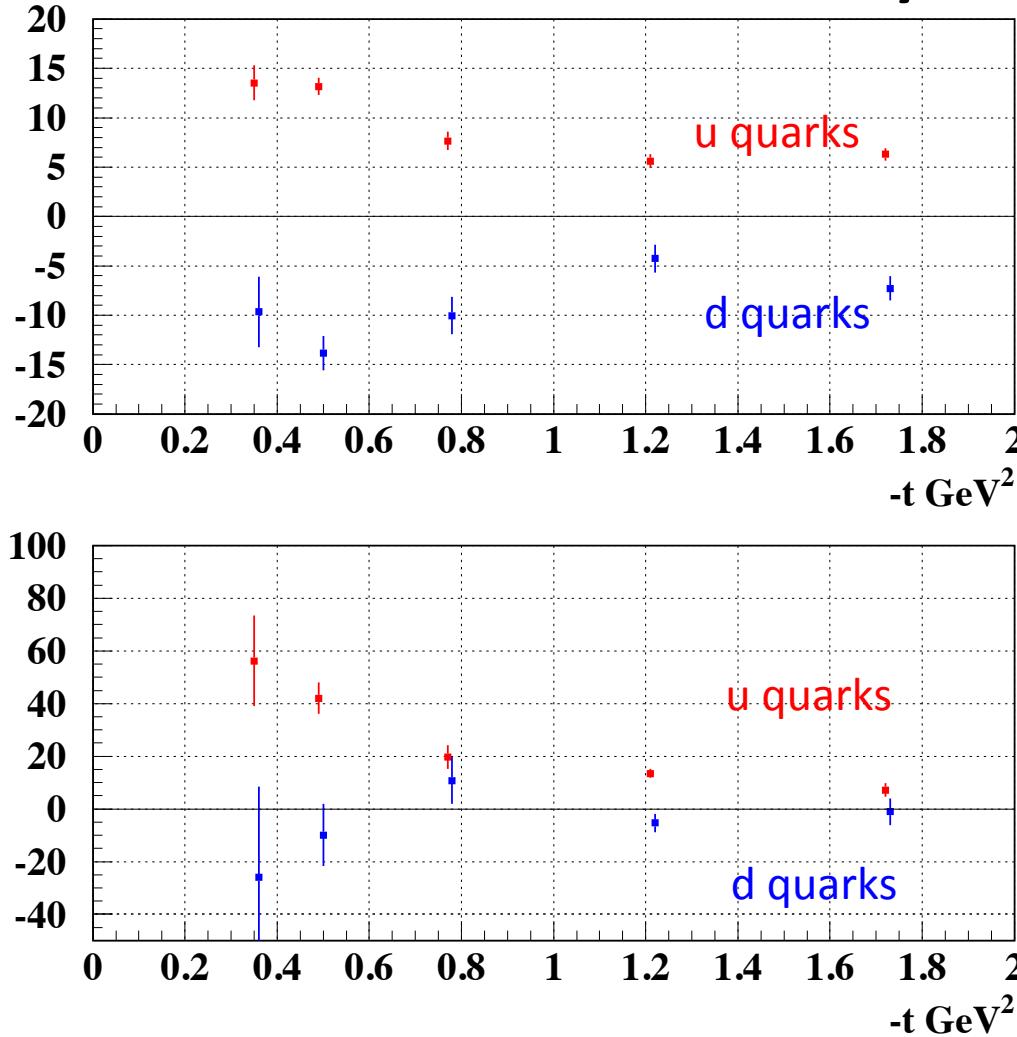
$$H_T^u = \frac{3}{2\sqrt{2}}[H_T^\pi + \sqrt{3}H_T^\eta]$$

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

- 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 E_T
- The u/d decomposition was done under simple assumption that the relative between u and d is 0 or 180 degrees.

Similar expressions for \bar{E}_T

Flavor Decomposition of the Transversity GPDs



- $\langle H_T \rangle^u$ 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.)
- $|\langle \bar{E}_T \rangle|^d$ is small in comparison with $|\langle \bar{E}_T \rangle|^u$

$Q^2=2.7 \text{ GeV}^2, x_B=0.34$

Summary

- The discovery of Generalized Parton Distributions has opened up a new and exciting avenue of hadron physics that needs exploration in dedicated experiments
- CLAS π^0 and η data supports the dominance of the transversity GPDs H_T and \bar{E}_T in the processes of the pseudoscalar meson electroproduction
- The generalized form factors $\langle H_T \rangle$ and $\langle \bar{E}_T \rangle$ are directly connected to the structure functions σ_T and σ_{TT} within handbag approach
- The combined π^0 and η data will provide the way for the flavor decomposition of transversity GPD

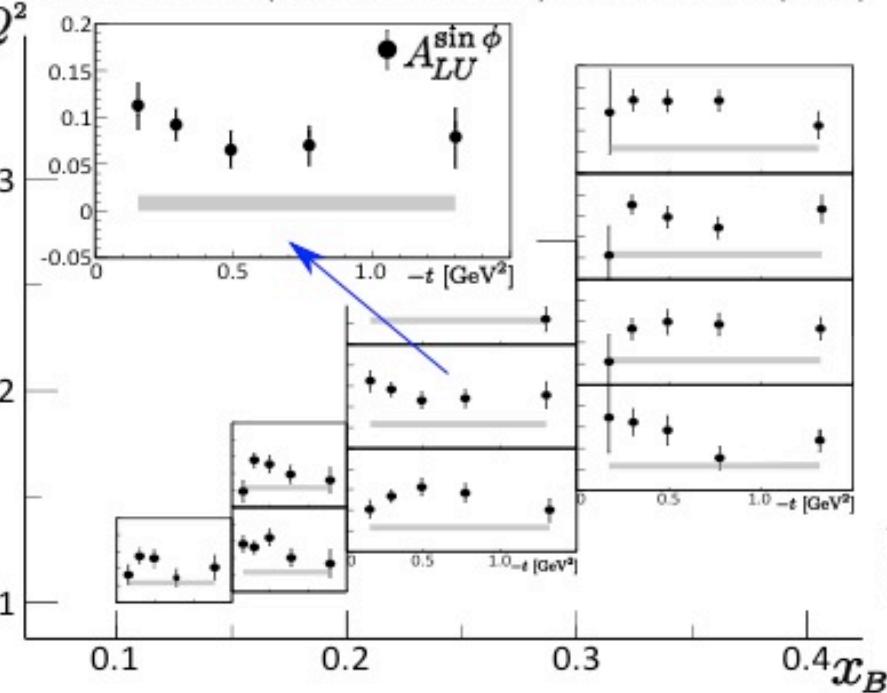
END

$ep \rightarrow ep\pi^0$: spin asymmetries



◆ Beam Spin Asymmetries

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



Dominated by transverse virtual photons contribution

↓
Unique sensitivity

for constraining the chiral-odd GPDs

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

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

$$A_{LL}^{\text{const}} \sigma_0 \sim |\langle H_T \rangle|^2$$

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

◆ Target and Double Spin Asymmetries

