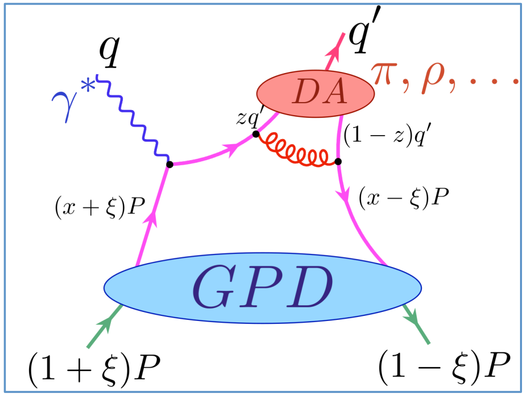
Deeply Virtual Meson Production and Transversity GPDs

Valery Kubarovsky

Jefferson Lab

Exclusive Meson Production and Short-Range Hadron Structure
January 22-24, 2015, Jlab

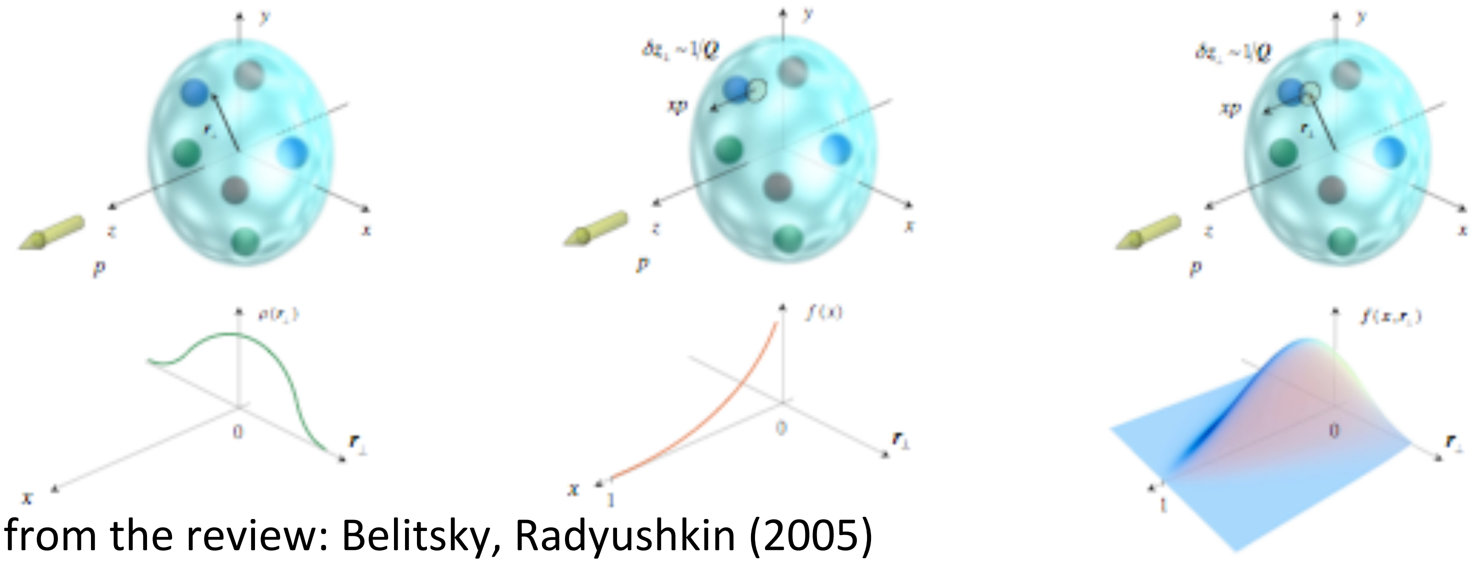
Outline



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

Description of hadron structure in terms of GPDs

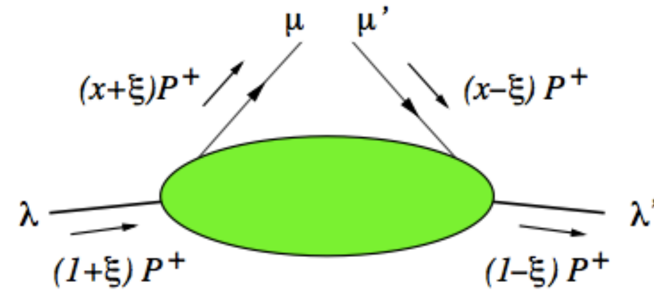
D. Mu¨ller ’94, X. Ji ‘96, A. Radyushkin ‘96



Picture from the review: Belitsky, Radyushkin (2005)

Nucleon form factors	*Structure functions*	*GPDs*
transverse charge & current densities Nobel prize 1961- R. Hofstadter	quark longitudinal momentum (polarized and unpolarized) distributions Nobel prize 1990 –J.Friedman, H. Kendall, R. Taylor	correlated quark momentum distributions (polarized and unpolarized) in transverse space

Generalized Parton Distributions



- GPDs are functions of three kinematic variables: x, ξ and t ,

  x-quark momentum fraction of the nucleon, skewedness $\xi = xB/(2-x_B)$, $t=(p-p')^2$.
- 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

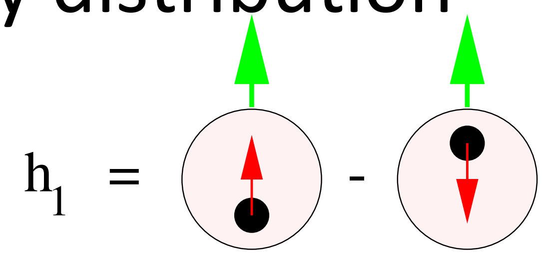
- Very little known about the chiral-odd GPDs
- Anomalous tensor magnetic moment

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

- (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

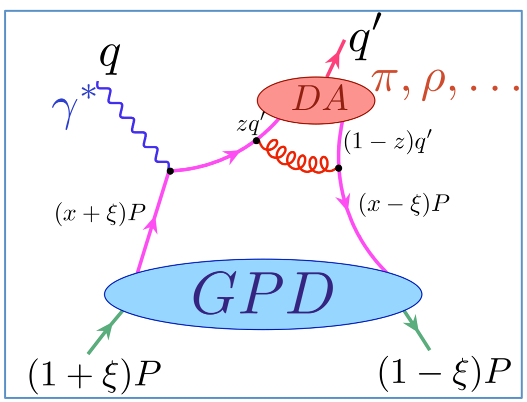
$$\gamma^* p \to p\pi^0$$

Structure functions and GPDs

$$\frac{d^2\sigma(\gamma^* p \to p\pi^0)}{dt d\phi_\pi} = \frac{1}{2\pi}\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \epsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT}}{dt}\cos\phi\right]$$

Leading twist σ_L

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^4}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2 \mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$$



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

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

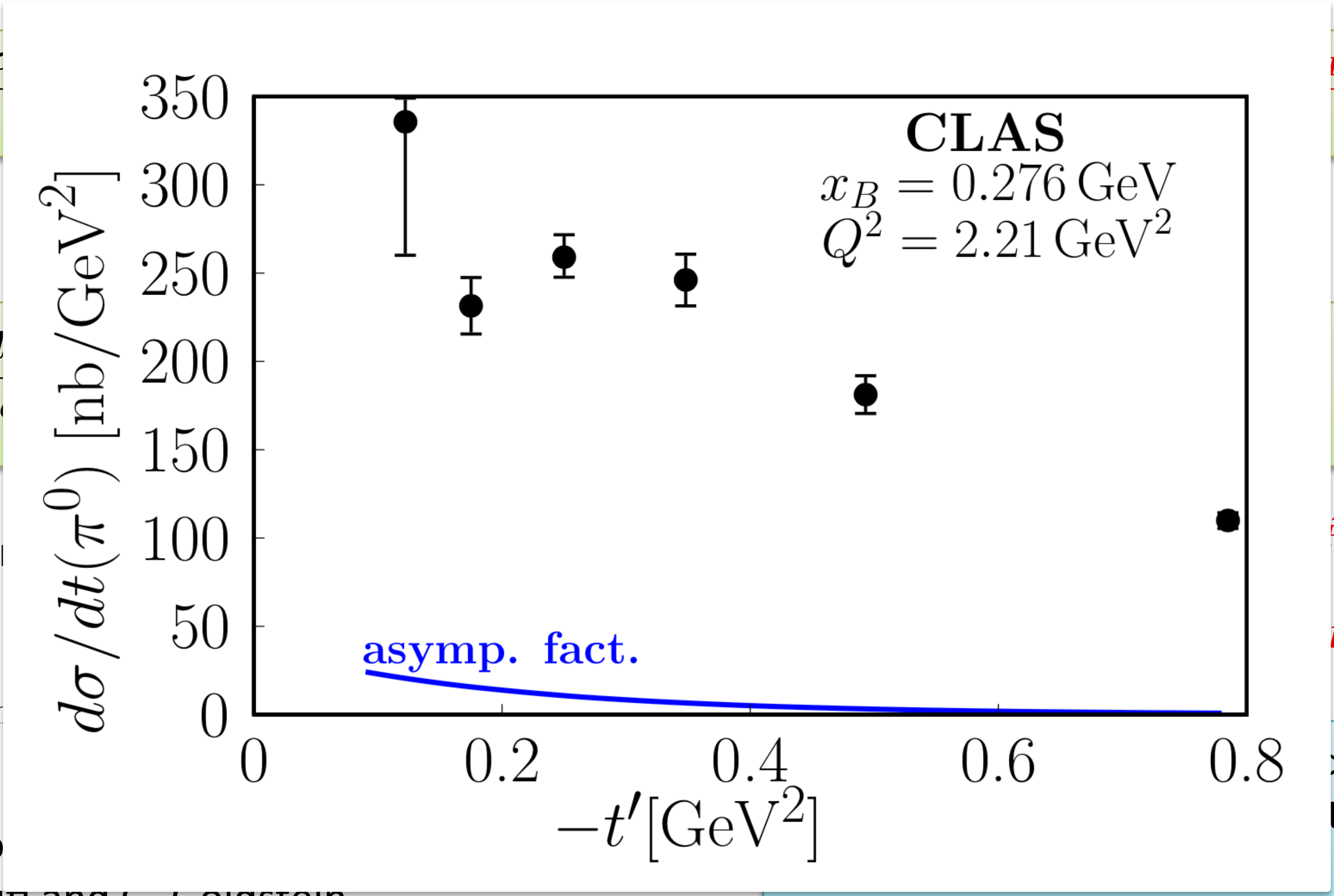
The brackets <F> denote the convolution of the elementary process with the GPD F (generalized form factors)

Structure functions and GPDs

$\frac{d^2 c}{}$ ... $\frac{}{} \cos\phi \Big]$

Lead

d ...



σ_L suppr ... $\tilde{H}(x,\xi,t)$

$\tilde{H}^\pi =$ ... $\tilde{E}(x,\xi,t)$

$\tilde{H}^u$ an

...onvolution
...th the GPD F

S. Go

S. Liuti and G. Goldstein

Structure functions and GPDs

$$\frac{d^2\sigma(\gamma^* p \to p\pi^0)}{dt d\phi_\pi} = \frac{1}{2\pi}\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \epsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT}}{dt}\cos\phi\right]$$

Leading twist σ_L

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^4}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2 \mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$$

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 signes

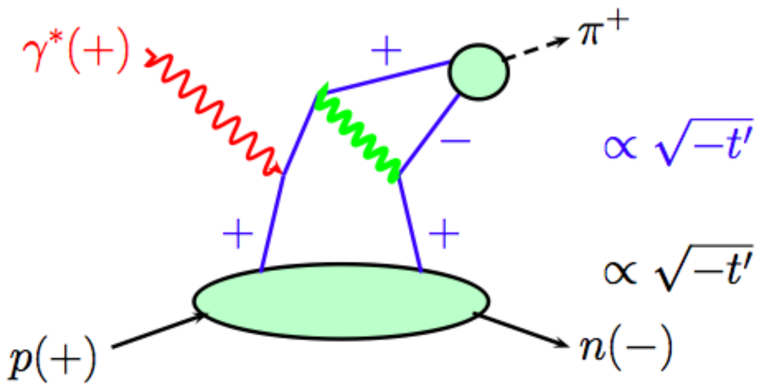
$$\left\langle\tilde{H}\right\rangle = \sum_\lambda \int_{-1}^{1} dx M(x,\xi,Q^2,\lambda)\tilde{H}(x,\xi,t)$$

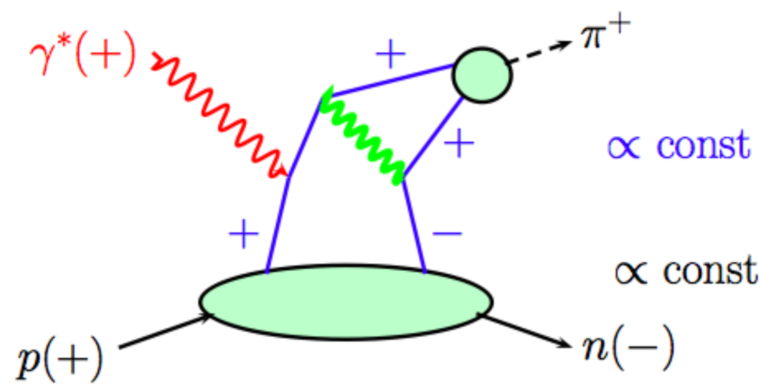
$$\left\langle\tilde{E}\right\rangle = \sum_\lambda \int_{-1}^{1} dx M(x,\xi,Q^2,\lambda)\tilde{E}(x,\xi,t)$$

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

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

Transversity in electroproduction of pseudoscalar mesons





Leading twist pion wave function
dynamically suppressed

$$M_{0-,++} \propto (t_{\min} - t)$$

Twist-3 pion wave function suppressed by μ_π / Q , however

$$\mu_\pi = \frac{m_\pi^2}{m_u + m_d} \approx 2.5GeV$$

(enhanced by chiral condensate)

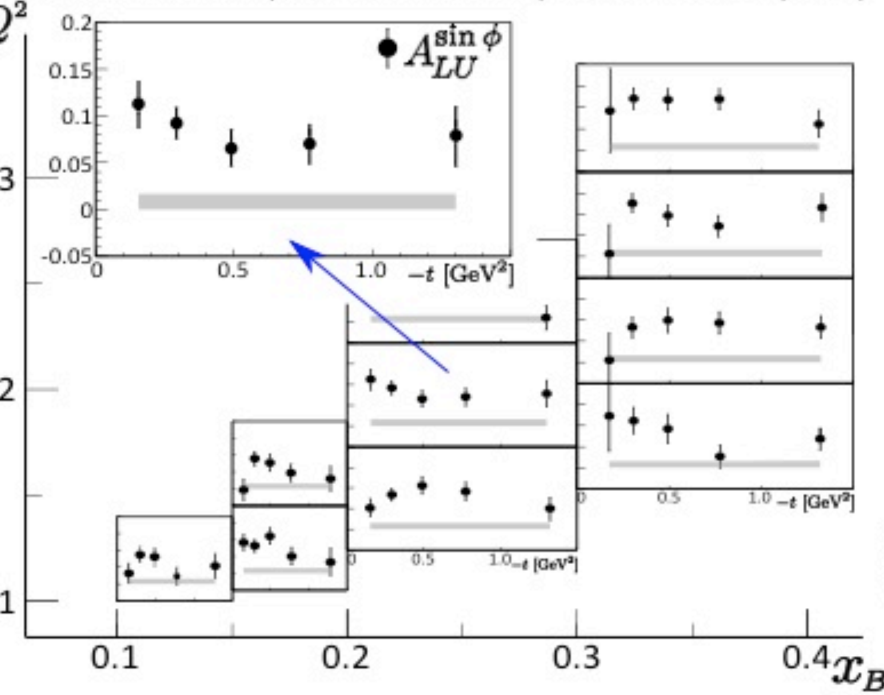
$$M_{0-,++} \propto const$$

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

CEBAF Large Acceptance Spectrometer

❖ Beam Spin Asymmetries

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



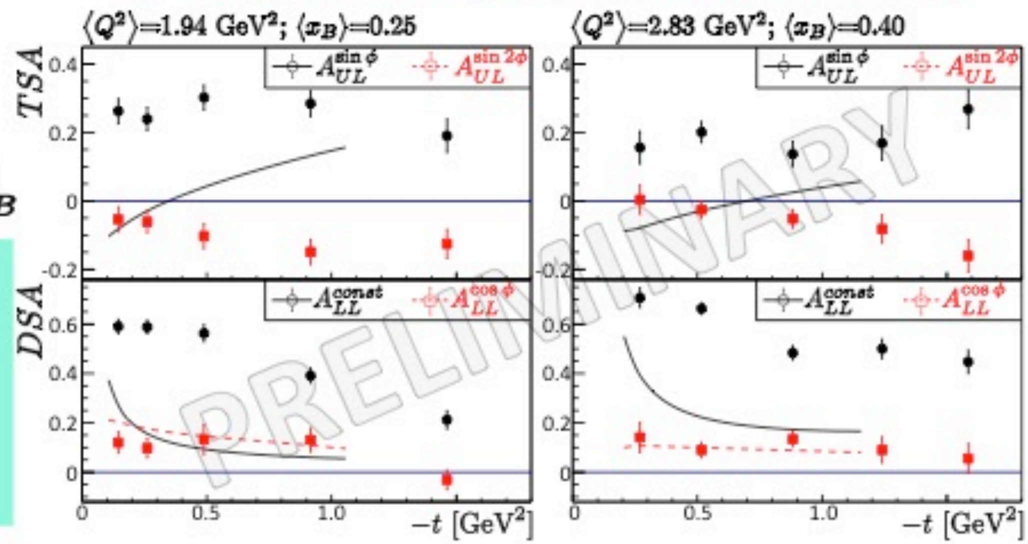
$$A_{LU}^{\sin\phi}\sigma_0 \sim \mathrm{Im}\left[\langle H_T\rangle^* \langle \tilde{E}\rangle\right]$$

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

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

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

❖ Target and Double Spin Asymmetries



Dominated by transverse virtual photons contribution

⇓

Unique sensitivity

for constraining the chiral-odd GPDs

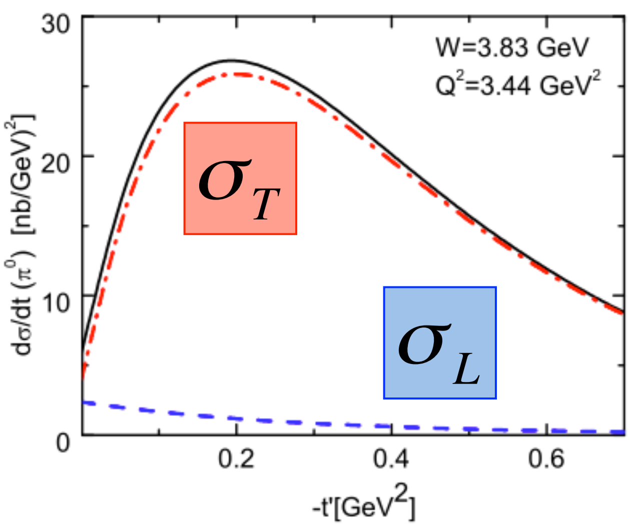
A. Kim, to be published

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

Structure functions and GPDs

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

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



Transversity dominance

Transversity GPD model

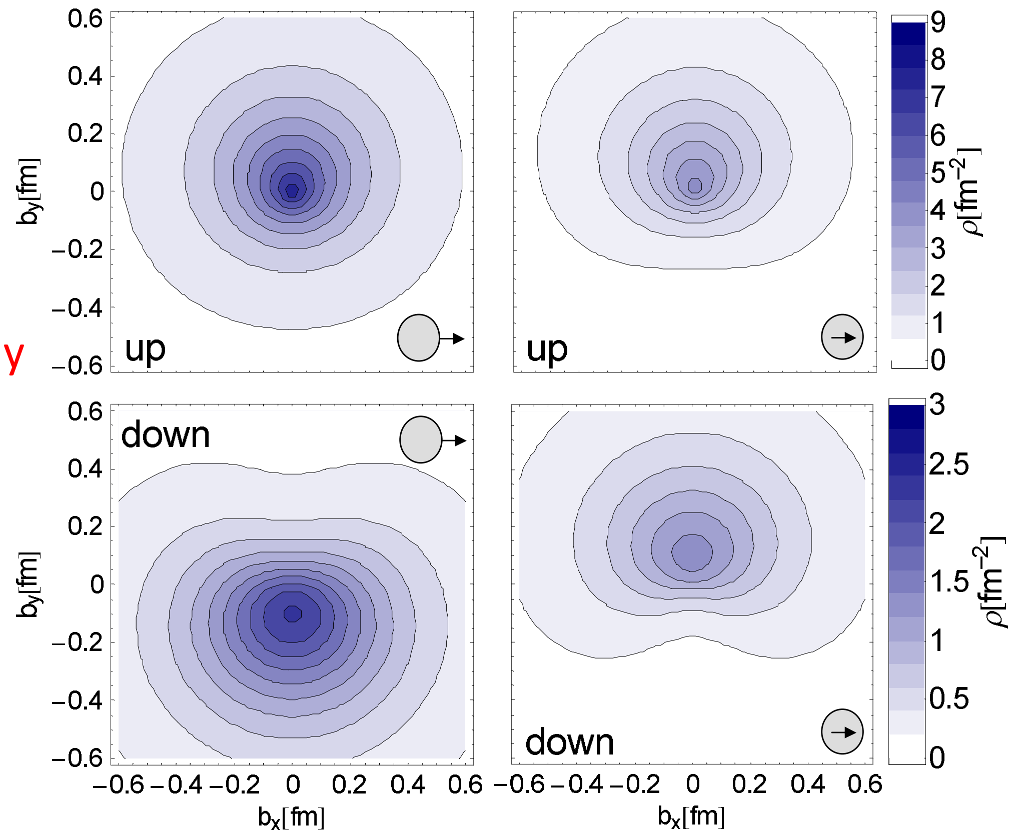
S. Goloskokov and P. Kroll

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 $\bar{E}_T=2\tilde{H}_T+E_T$
- Direct access to the Transversity GPDs

Transverse Densities for u and d Quarks in the Nucleon

Strong distortions for unpolarized quarks in transversely polarized nucleon



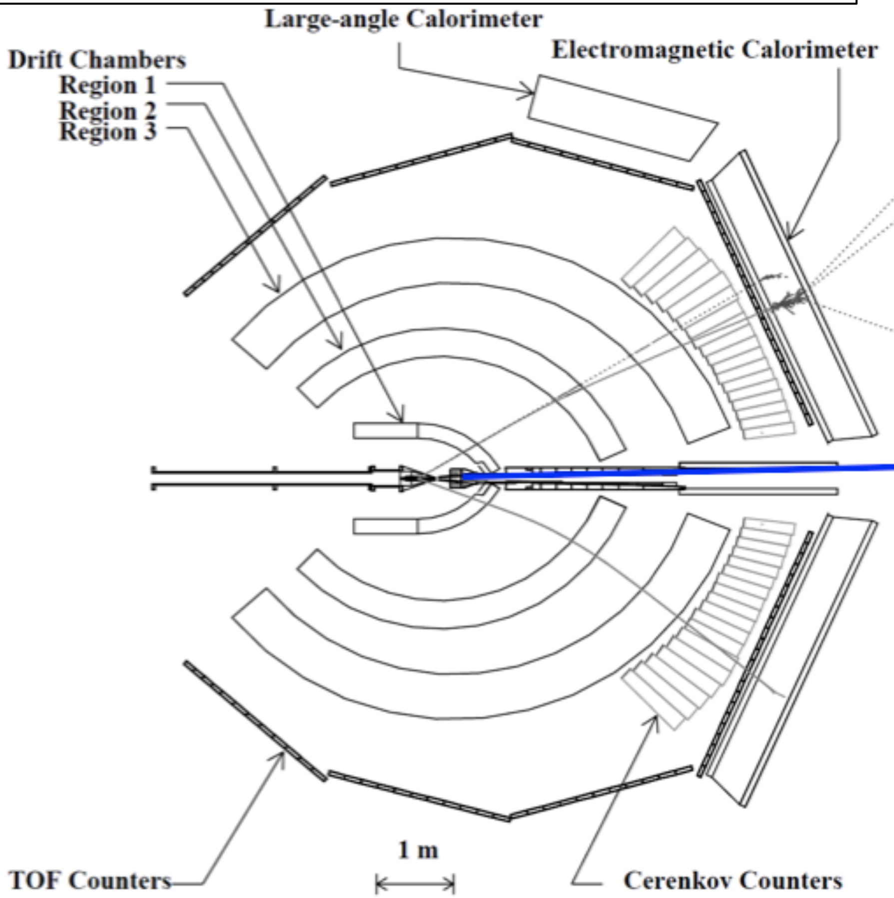
Strong distortions for transversely polarized quarks in an unpolarized nucleon

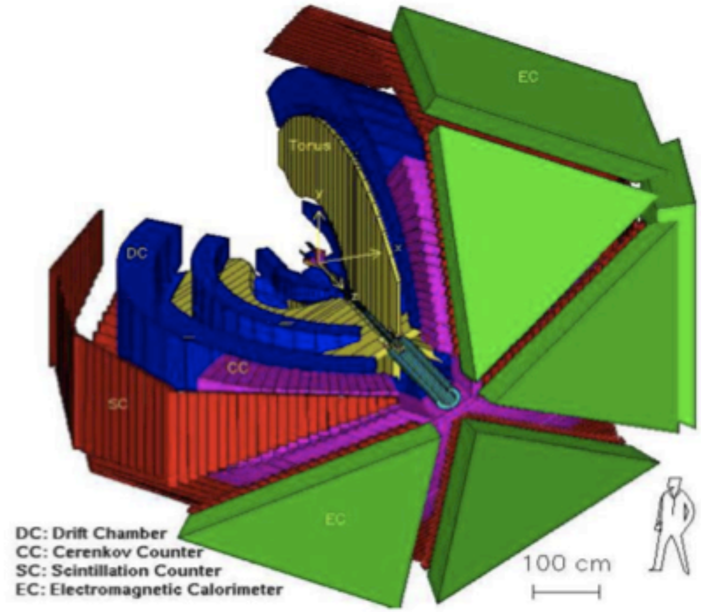
Described by E

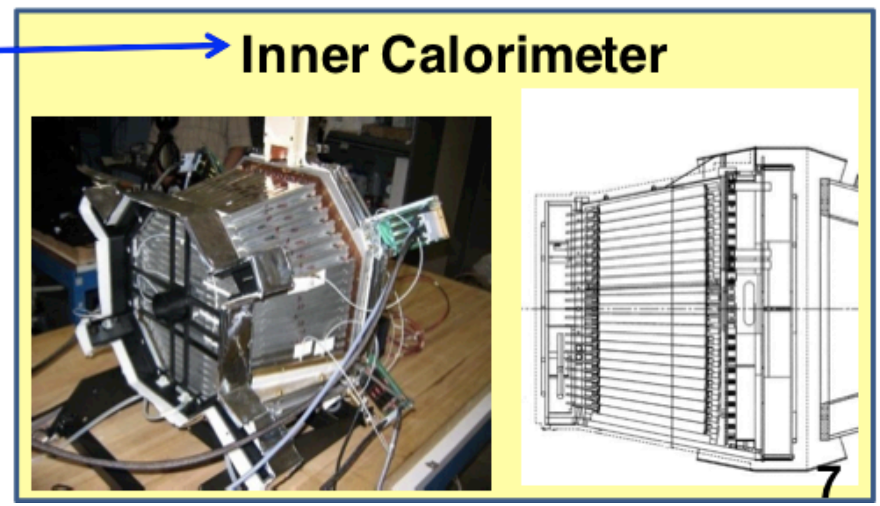
Described by $\bar{E}_T = 2\tilde{H}_T + E_T$

Gockeler et al, hep/lat/0612032

e1-dvcs (2005)







CLAS Lead Tungstate Electromagnetic Calorimeter

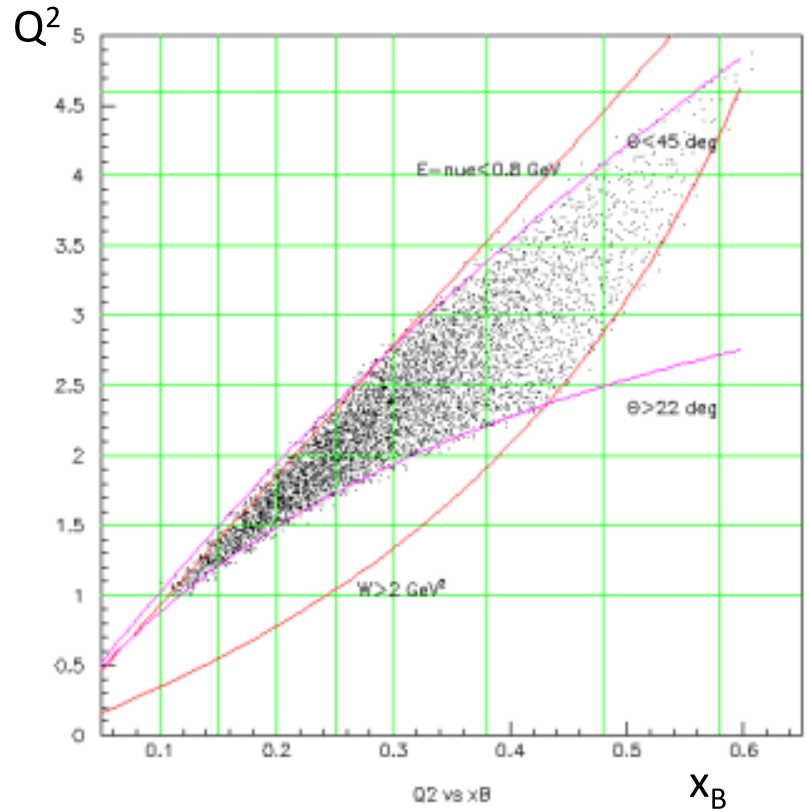
424 crystals, 18 RL,
Pointing geometry,
APD readout

4 Dimensional Grid

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

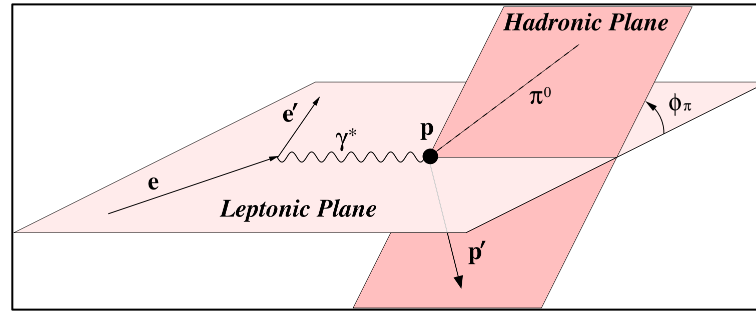
Rectangular bins are used.

- 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

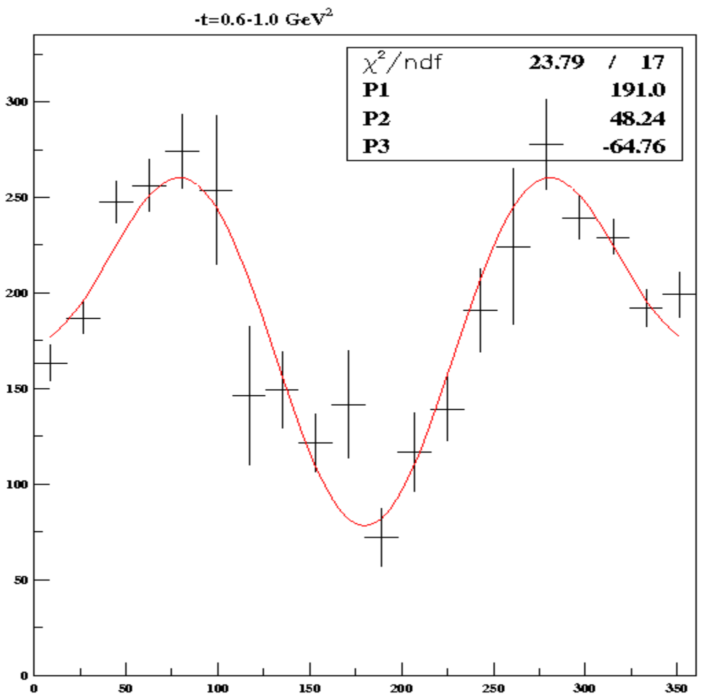


Structure Functions

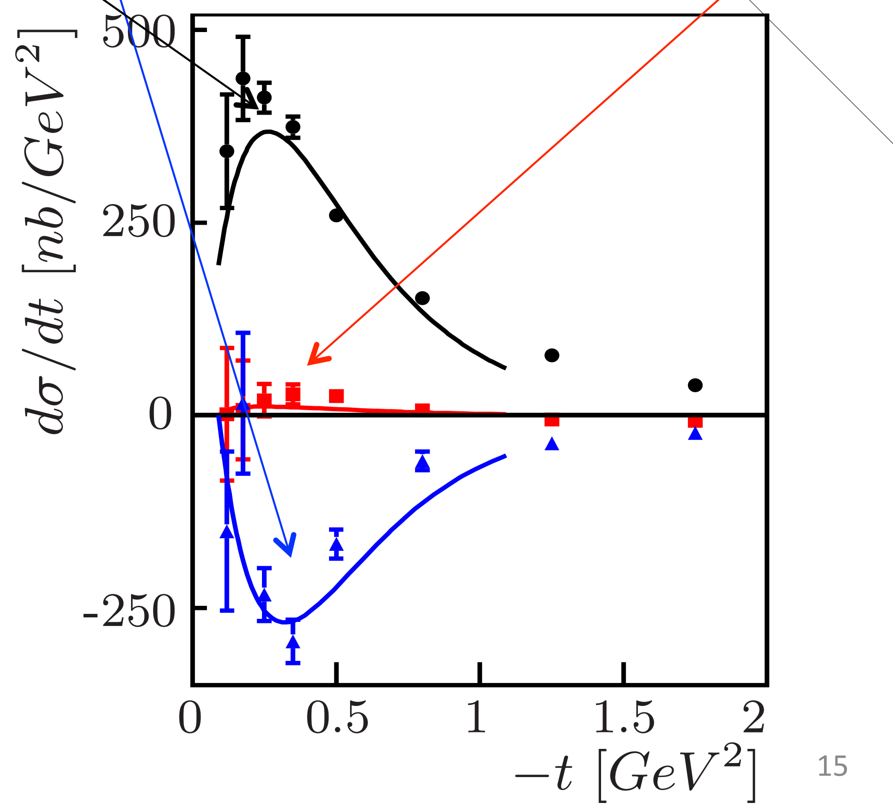
$\sigma_U = \sigma_T + \varepsilon\sigma_L \quad \sigma_{TT} \quad \sigma_{LT}$



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



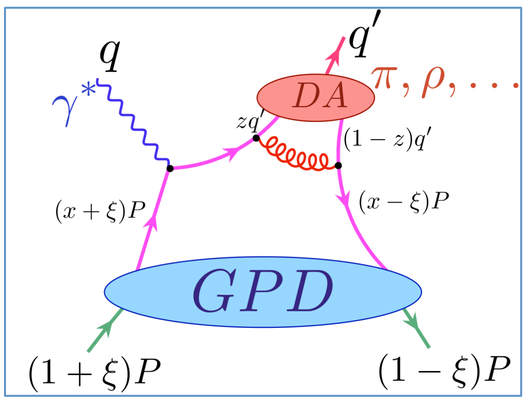
φ distribution

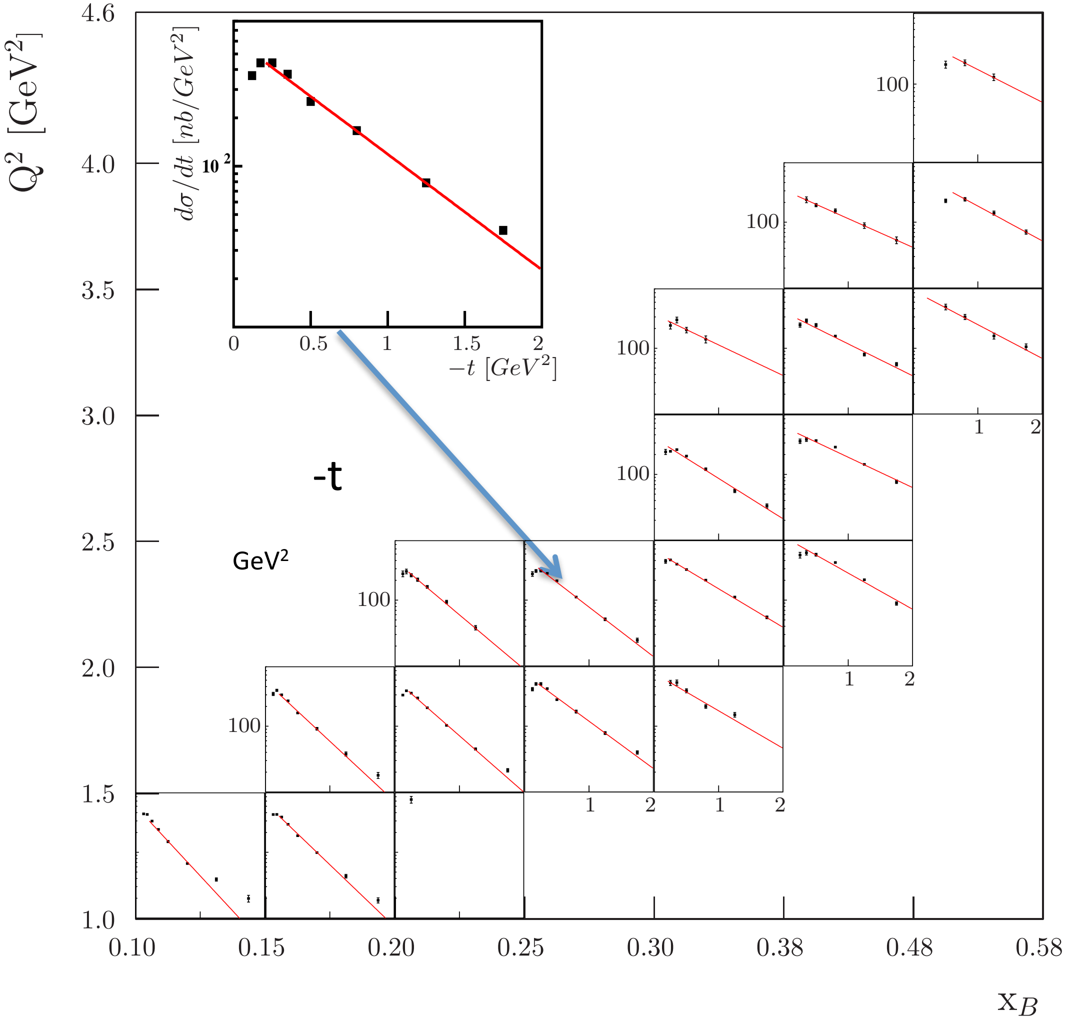


-t

$d\sigma_U/dt$

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

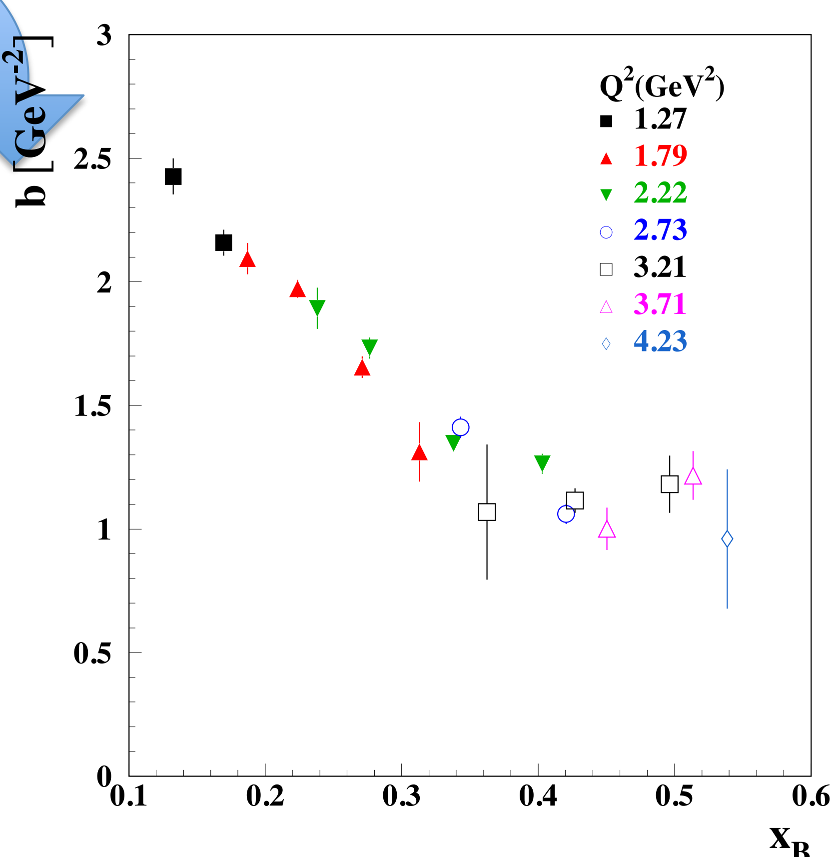




t-slope parameter: x_B dependence

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

$$R_T = b/(1 - x_B)$$

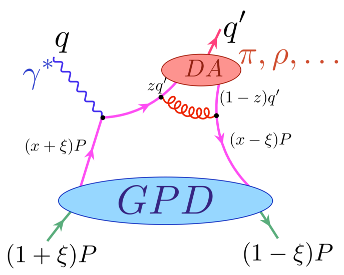


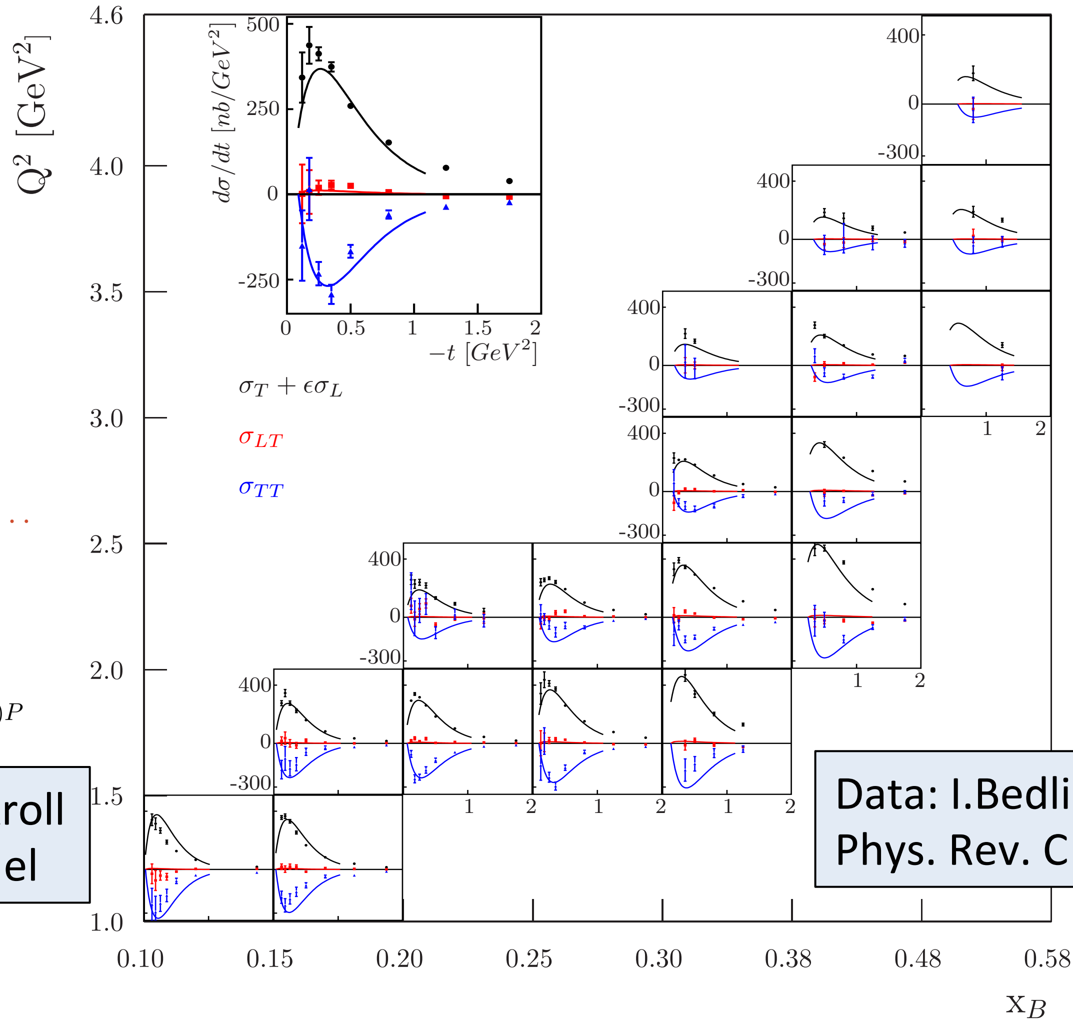
The slope parameter is decreasing with increasing x_B. The Q^2 dependence is weak. Looking to this picture we can say that proton's transverse radius shrinks as x→1.

Structure Functions

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

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





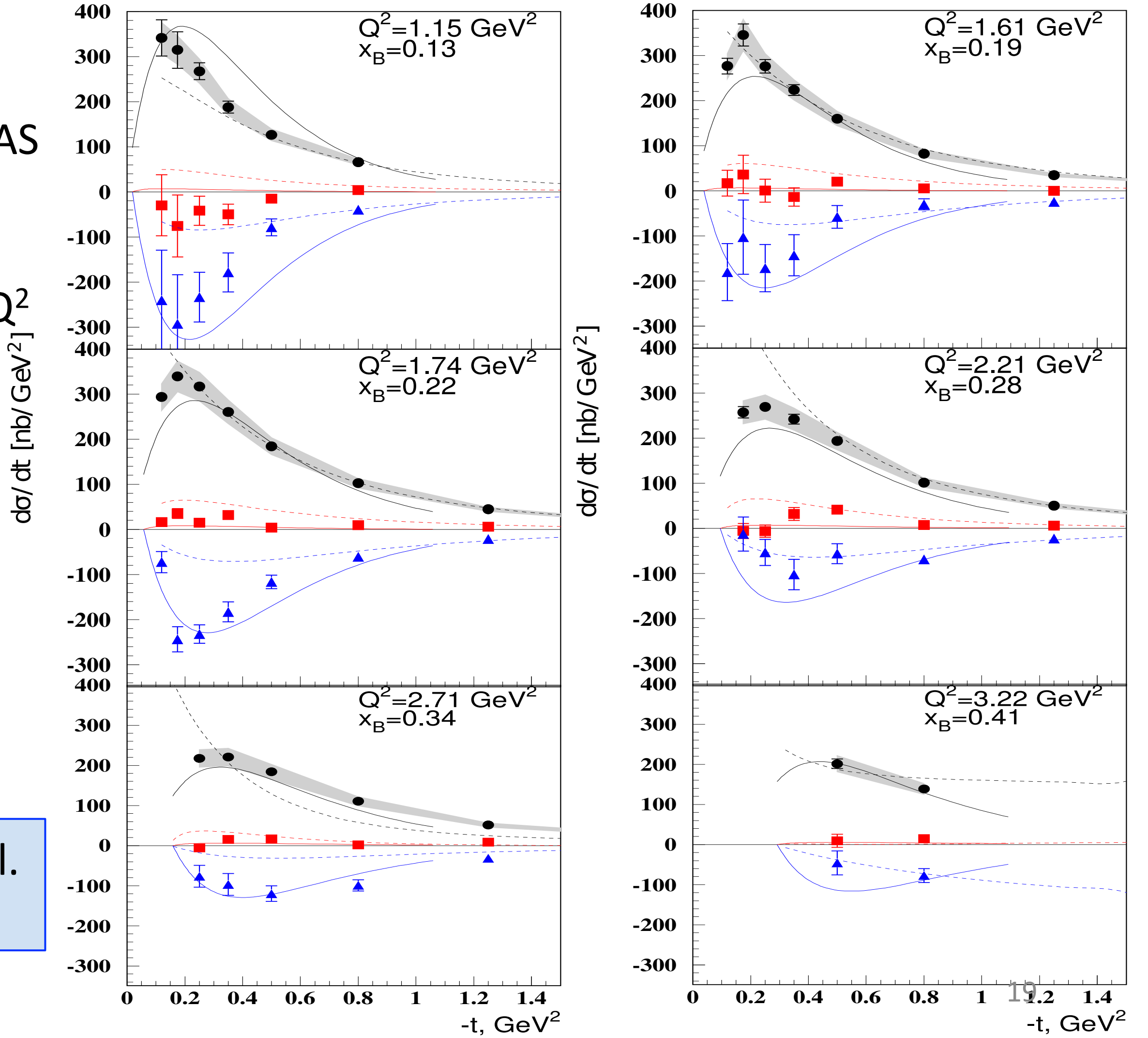
Curves: Goloskokov, Kroll
Transversity GPD model

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

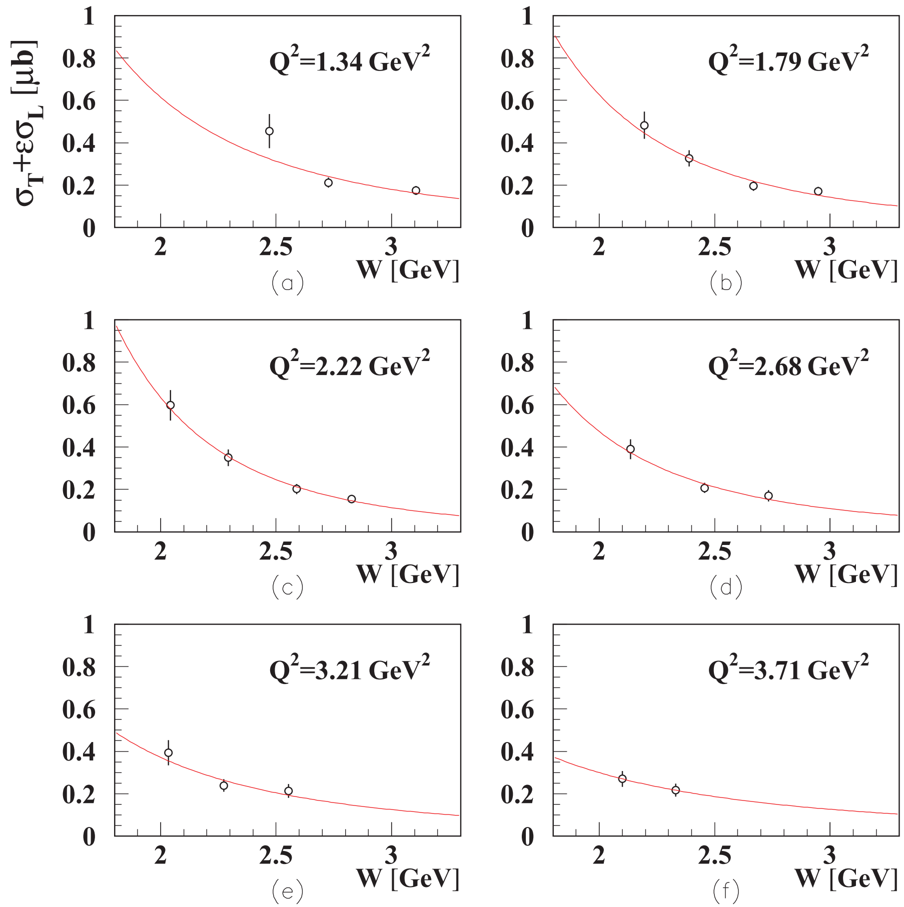
- ***Transversity* GPDs** H_T and $\bar{E}_T = 2\tilde{H}_T + E_T$ dominate in CLAS kinematics.
- The model was optimized for low x_B and high Q^2. The corrections t/Q^2 were omitted.
- The model successfully describes CLAS data even at low Q^2
- Pseudoscalar meson production provides unique possibility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



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

W-dependence of the total cross section $\sigma_{tot}(Q^2,W)(\gamma^*p)$

EXCLUSIVE π^0 ELECTROPRODUCTION AT $W > 2$ ... PHYSICAL REVIEW C **90**, 025205 (2014)



Spin Asymmetries

$$\frac{d^2\sigma(\gamma^* p \to p\pi^0)}{dt d\phi_\pi} = \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \epsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{LT}}{dt} \cos\phi$$
$$+ P_b \sqrt{2\epsilon(1-\epsilon)} \frac{d\sigma_{LT'}}{dt} \sin\phi$$
$$+ P_t \left(\sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{UL}^{\sin\phi}}{dt} \sin\phi + \epsilon \frac{d\sigma_{UL}^{\sin 2\phi}}{dt} \sin 2\phi \right)$$
$$+ P_b P_t \left(\sqrt{1-\epsilon^2} \frac{d\sigma_{LL}^{const}}{dt} + \sqrt{2\epsilon(1-\epsilon)} \frac{d\sigma_{LL}^{\cos\phi}}{dt} \cos\phi \right)$$

$$\frac{d\sigma_T}{dt} = \frac{d\sigma_{LL}^{const}}{dt} - \frac{d\sigma_{TT}}{dt}$$

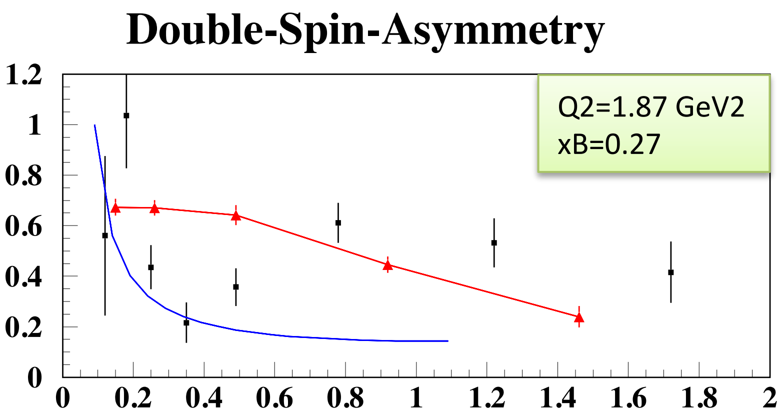
Kroll, Goloskokov

$$A_{LL}^{const} = 1 + \frac{d\sigma_{TT}/dt}{d\sigma_T/dt}$$

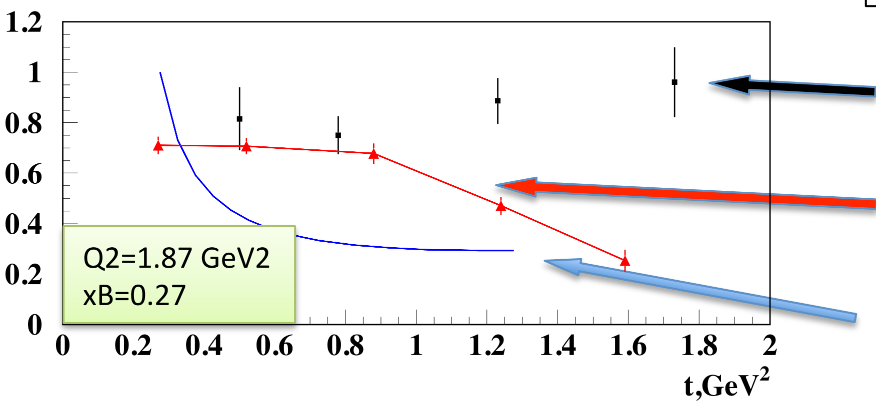
- Constant term of the double-spin asymmetries may be estimated from unpolarized data
- Compare with the asymmetry extracted from polarized data (A.Kim)

Double Spin Asymmetry

$$A_{LL}^{const} = 1 + \frac{d\sigma_{TT}/dt}{d\sigma_T/dt}$$



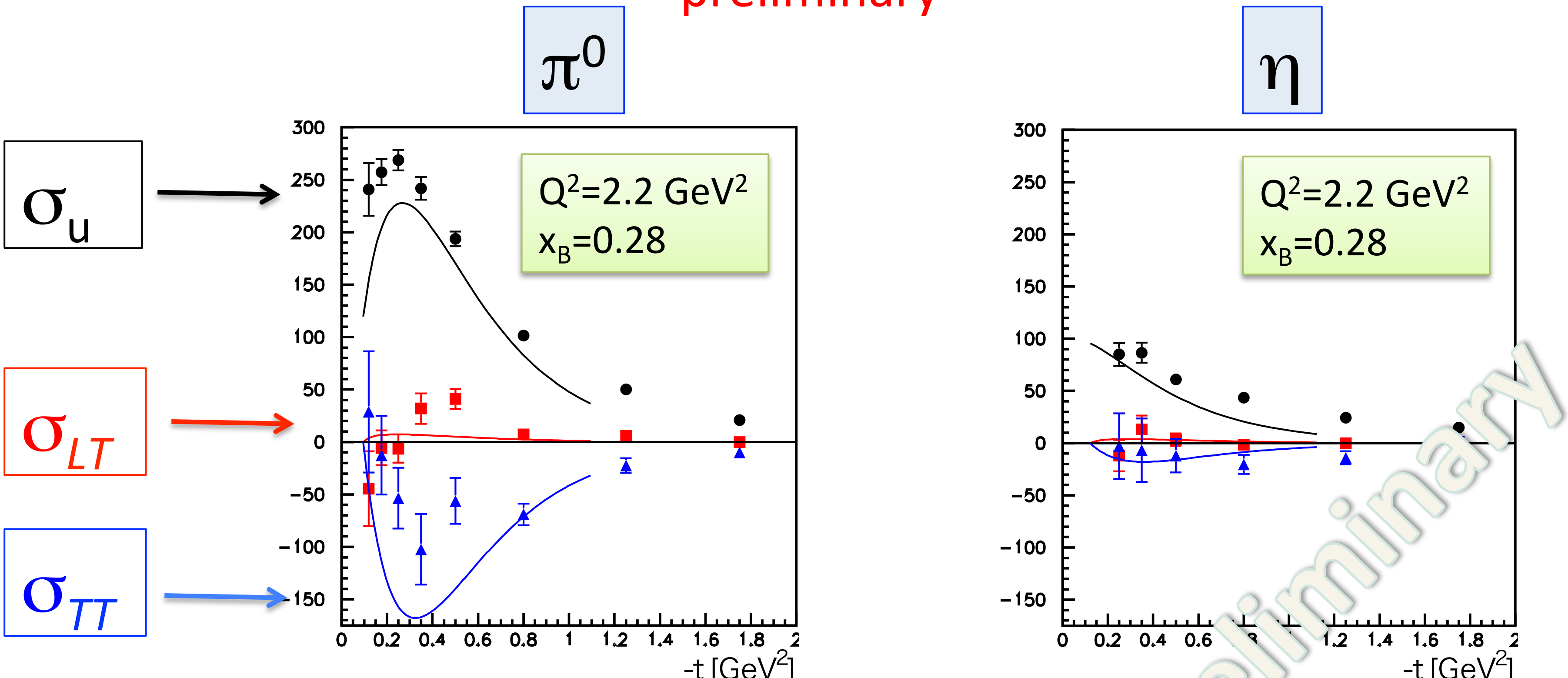
- Double-spin asymmetries from unpolarized and polarized data are consistent
- Theory does not describe data. The main reason for tjis inconsistency is coming from the theoretical description of the unpolarized structure functions
- Adjustment of the theory parameters will improve the description of the unpolarized data and at the same time double-spin asymmetry



- Asymmetry from the unpolarized data
- Asymmetry from polarized data
- Theoretical predictions (GK)

Comparison π^0/η

preliminary

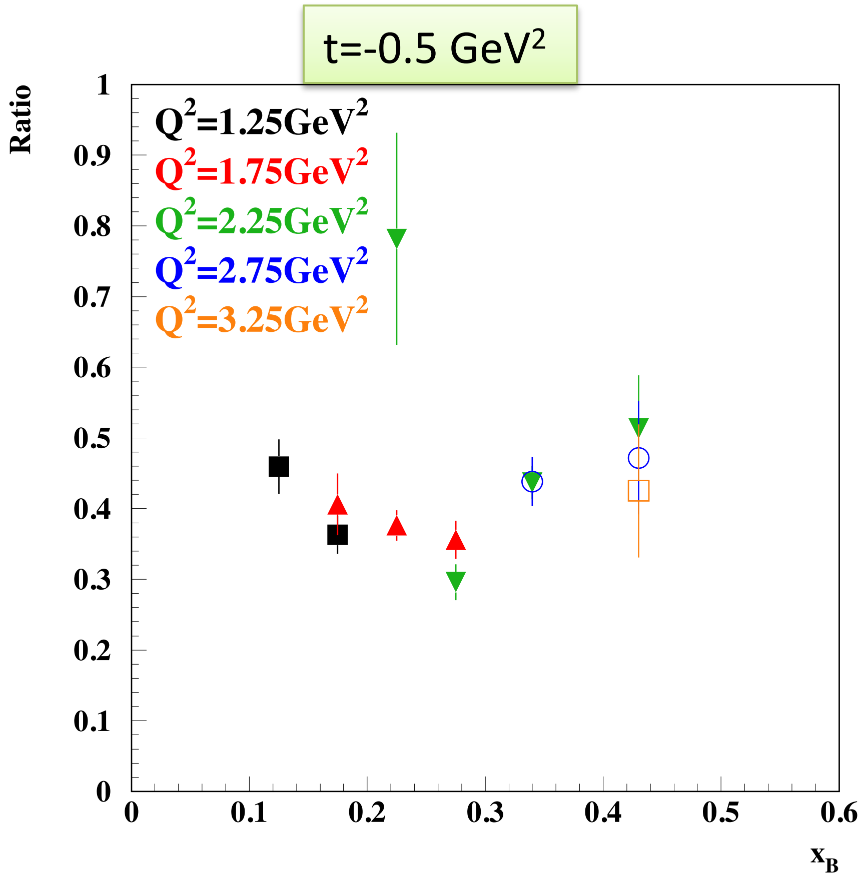


- $\sigma_U=\sigma_T+\varepsilon\sigma_L$ drops by a factor of 2.5 for η
- σ_{TT} drops by a factor of 10
- The GK GPD model (curves) follows the experimental data
- The statement about the transversity GPD dominance in the pseudoscalar electroproduction becomes more solid with the inclusion of η data

η/π^0 ratio

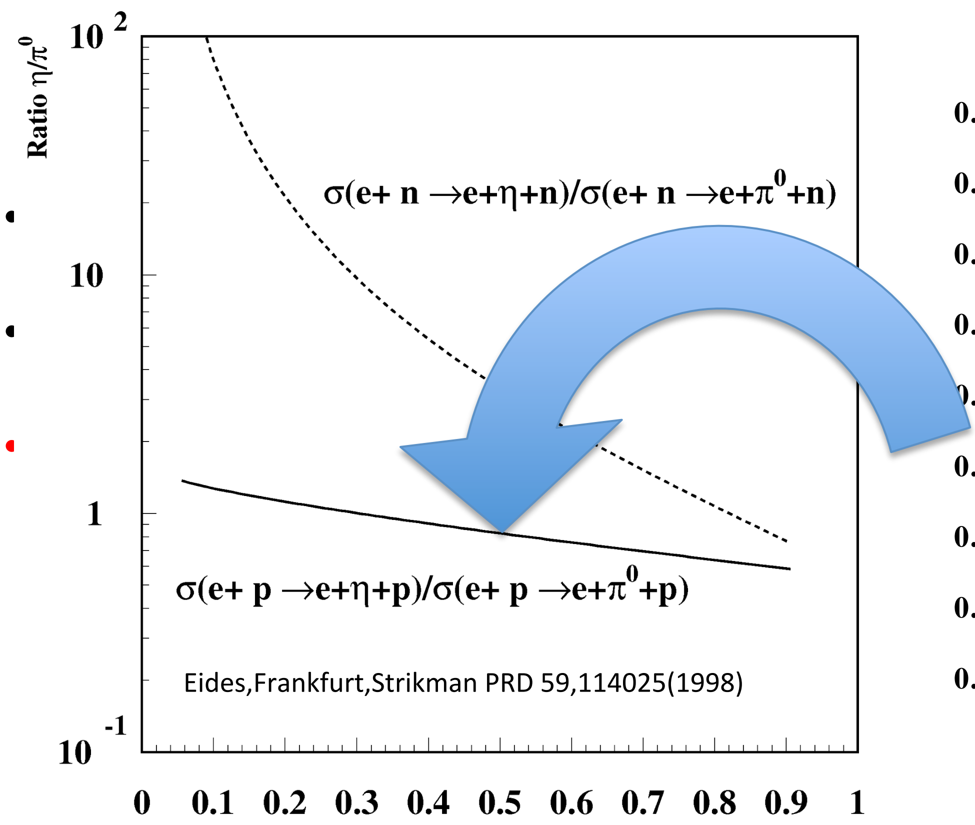
$$\frac{\sigma(ep \to ep\eta)}{\sigma(ep \to ep\pi^0)}$$

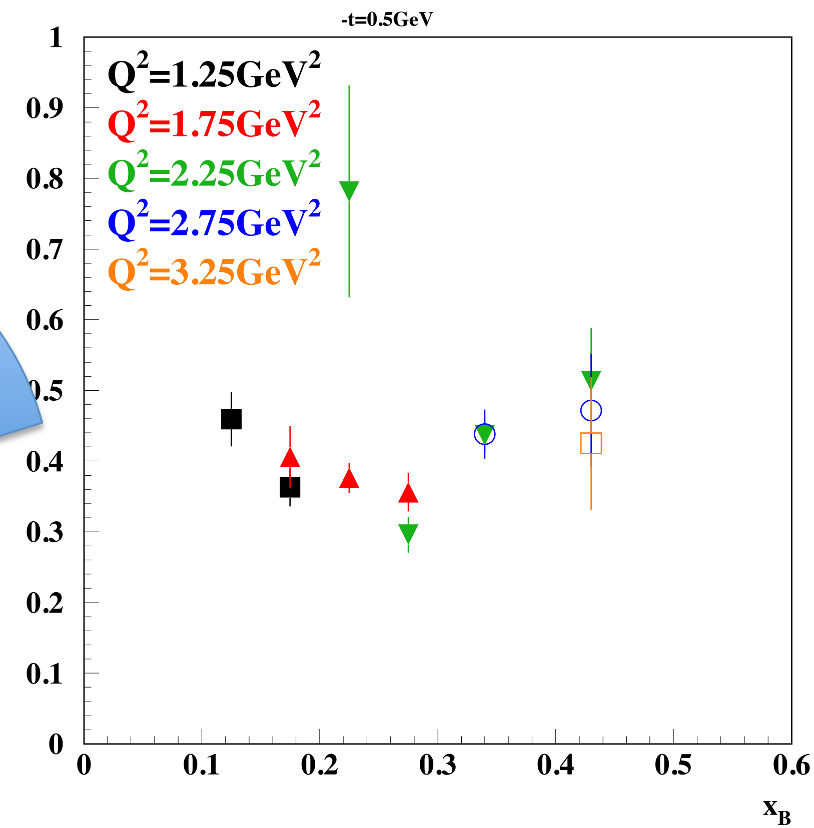
- The dependence on x_B and Q^2 is very weak.
- Chiral odd GPD models predict this ratio to be ~1/3 at CLAS kinematics
- Chiral even GPD models predict this ratio to be around 1 (at low –t).



η/π⁰ ratio

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



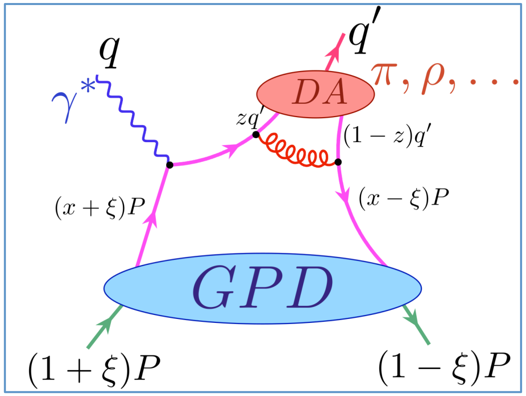


Theoretical prediction R=1 for the Chiral-even GPD models ($\sigma_L >> \sigma_T$)

Structure functions and GFFs

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

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



Goloskokov, Kroll
Transversity GPD model

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

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

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

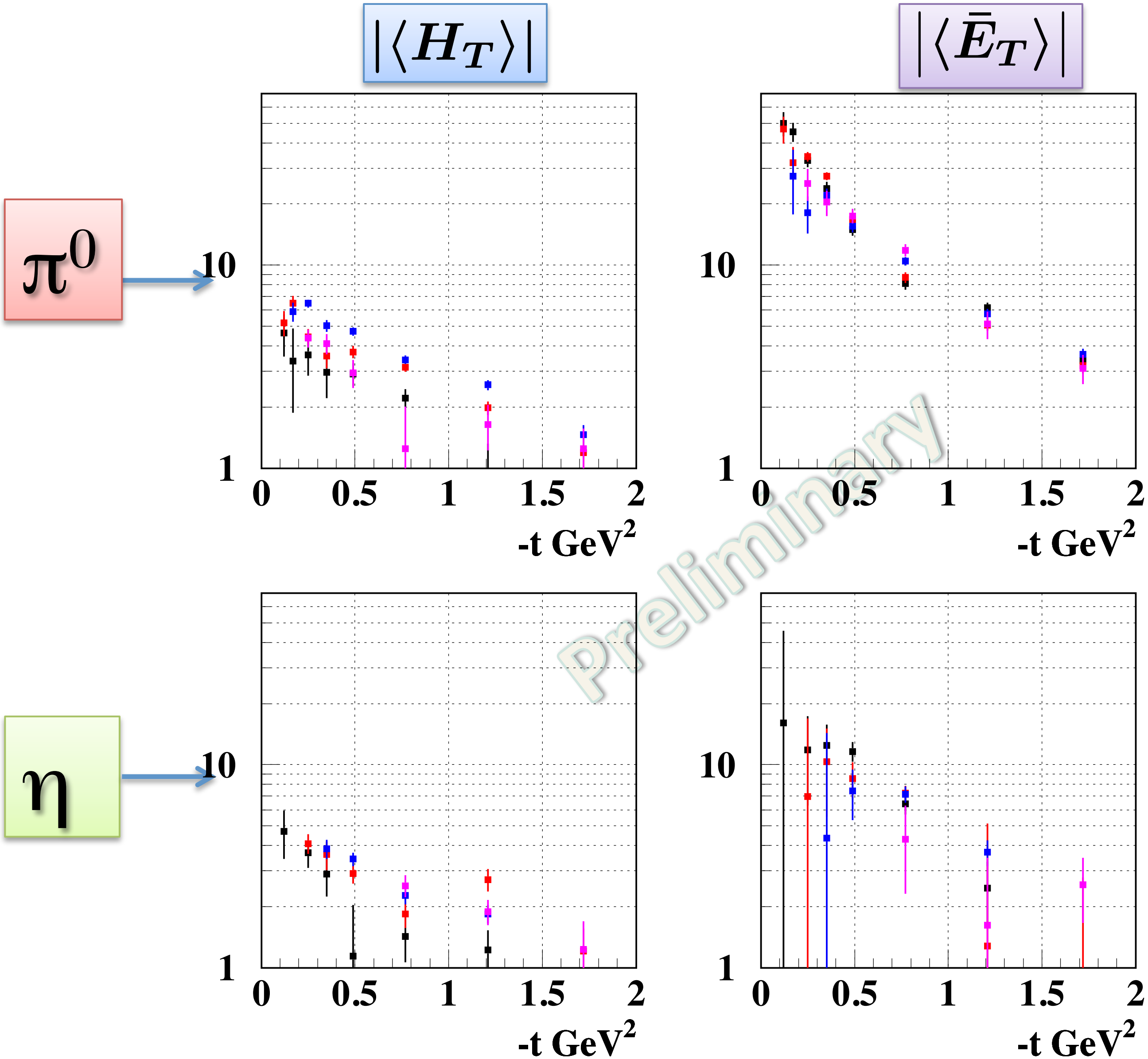
$$\langle \bar{E}_T\rangle = \Sigma_\lambda \int_{-1}^{1} dx M(x,\xi,Q^2,\lambda) \bar{E}_T(x,\xi,t)$$

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

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

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

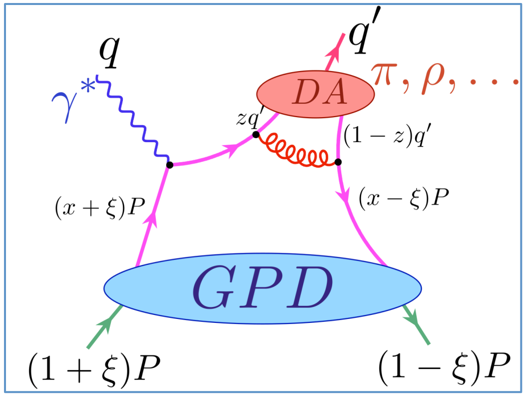
Generalized Form Factors

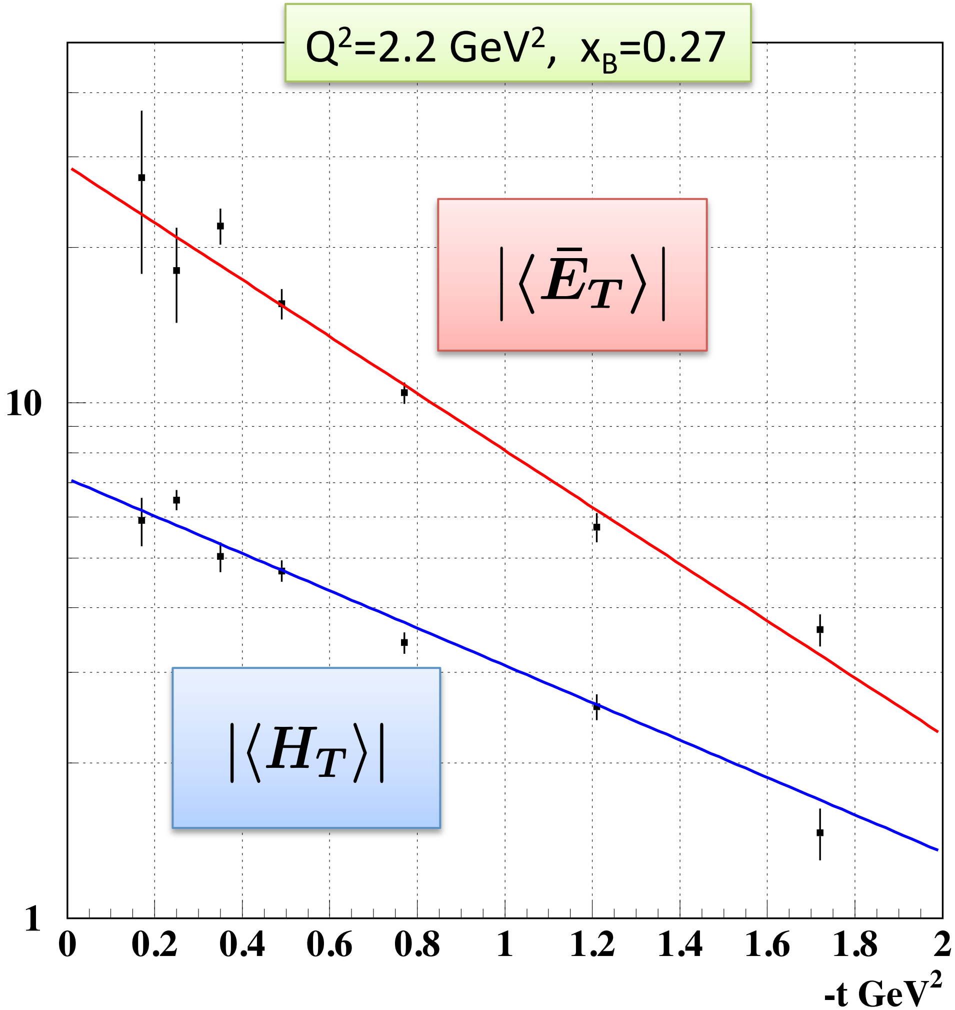


Q^2 GeV^2	x_B
1.2	0.15
1.8	0.22
2.2	0.27
2.7	0.34

- $\bar{E}_T$ > 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

π^0 Generalized Form Factors





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

- $|<E_T,H_T>| \sim e^{bt}$

- $b(E_T)=1.27\ GeV^{-2}$
- $b(H_T)=0.98\ GeV^{-2}$

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 $\bar{E}_T$

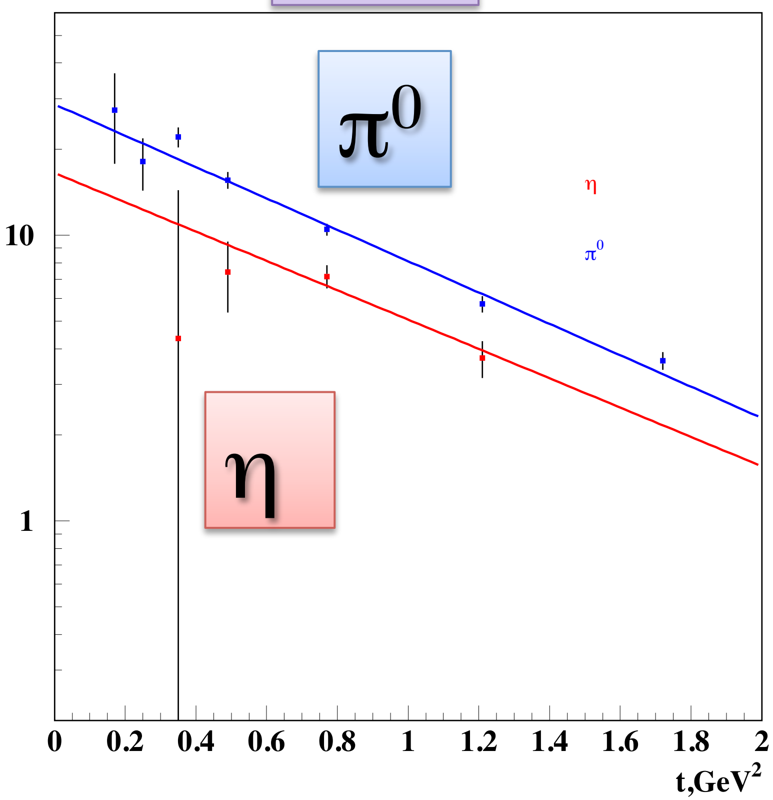
- GPDs appear in different flavor combinations for π^0 and η
- The combined π^0 and η data permit the flavor (u and d) decomposition for GPDs H_T and $\bar{E}_T$
- The u/d decomposition was done under simple assumption that the relative phase between u and d is 0 or 180 degrees.

π/η GPDs

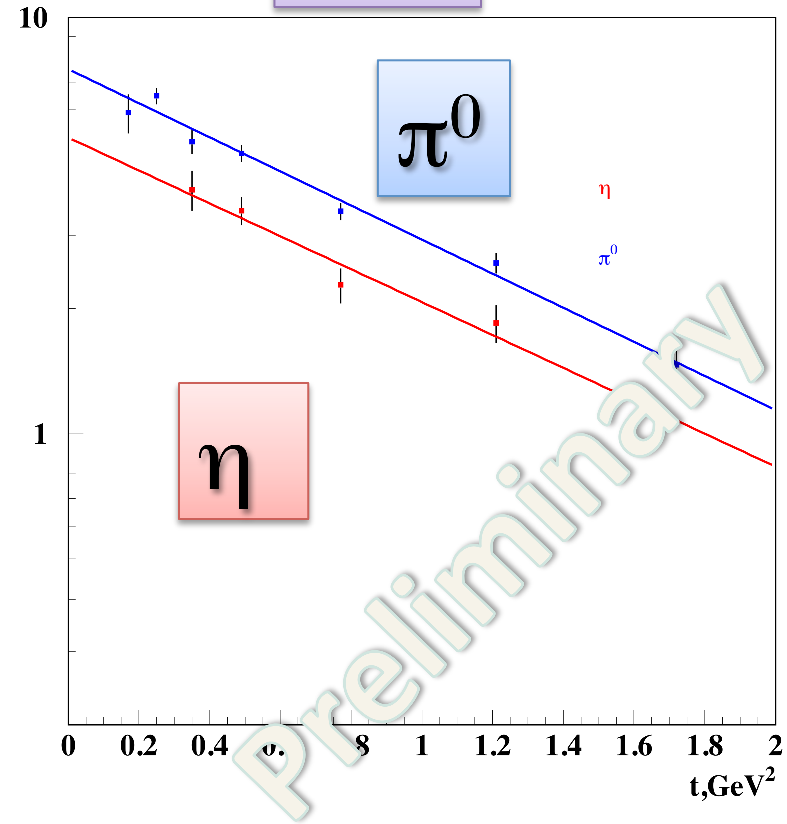
Q^2=2.2 GeV^2, x_B=0.27

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

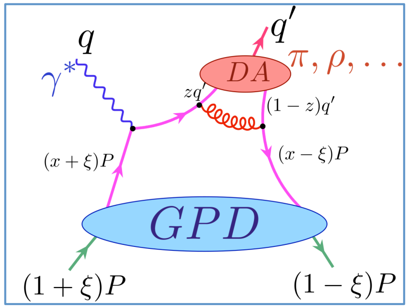
$|\langle \bar{E}_T \rangle|$



$|\langle H_T \rangle|$



η correction factor



$$|\eta\rangle = \cos\theta_8|\eta_8\rangle - \sin\theta_1|\eta_1\rangle$$
$$|\eta'\rangle = \sin\theta_8|\eta_8\rangle + cos\theta_1|\eta_1\rangle,$$

Octet-singlet mixing angle

$$\mu_{\pi^0} = \frac{m_{\pi^0}^2}{m_u + m_d},$$

$$\mu_{\eta 8} = \frac{3m_{\eta 8}^2}{m_u + m_d + 4m_s}$$

Chiral condensate

$$f_8 = 1.26 f_\pi$$
$$f_1 = 1.17 f_\pi$$

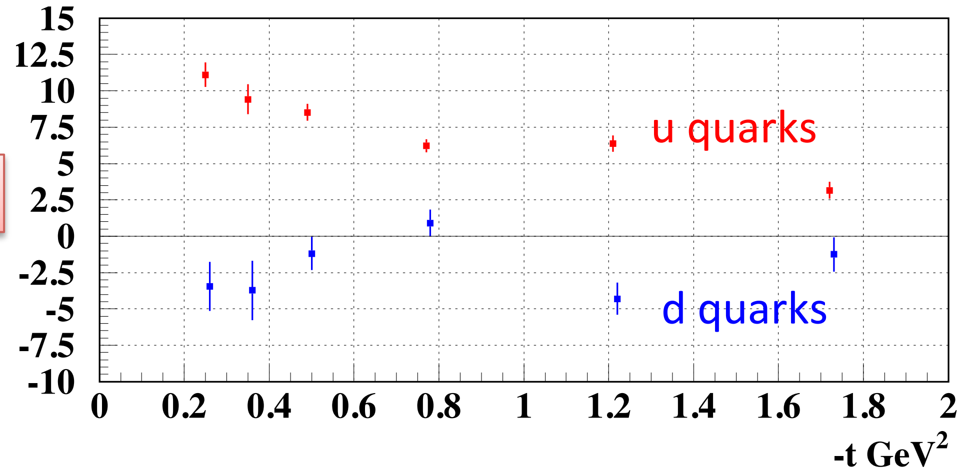
Decay constants

$$F_i^\eta = F_i^8 \left(\cos\theta_8 - \sqrt{2}\frac{\mu_1}{\mu_8}\frac{f_1}{f_8}\sin\theta_1\right)\frac{f_8}{f_{\pi^0}}\frac{\mu_8}{\mu_{\pi^0}} = \frac{F_i^8}{k_\eta}$$

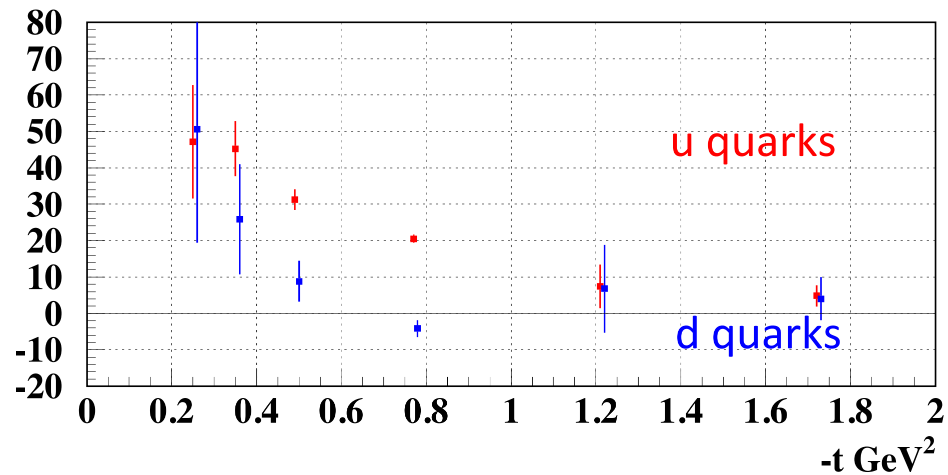
$1/K_\eta=1.16$

Flavor Decomposition of the Transversity GPDs

$\langle H_T \rangle$



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



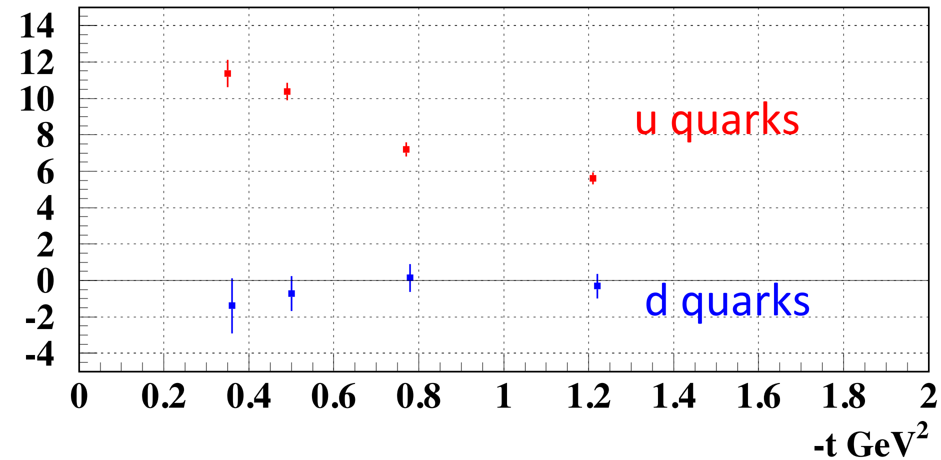
Q^2=1.8 GeV^2, x_B=0.22

- $\langle H_T \rangle^u$ 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
- Decisions shown with positive values of u-quark's GPDs only

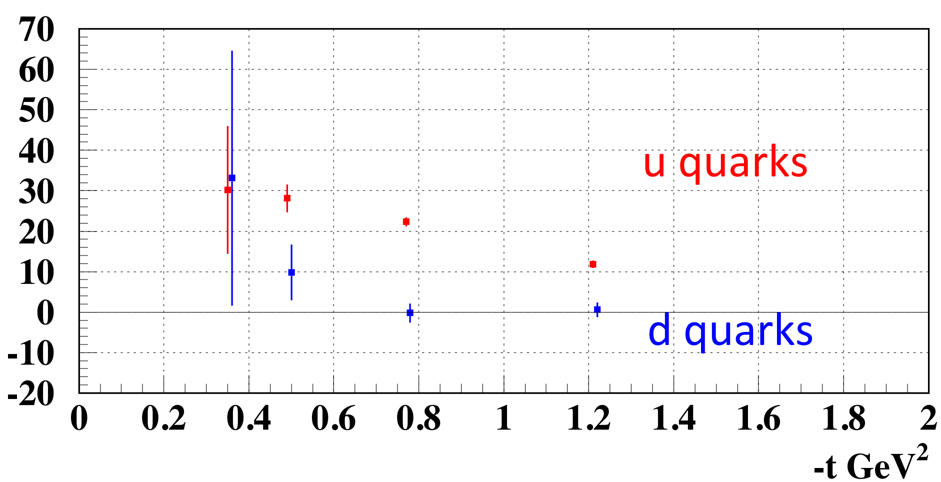
Flavor Decomposition of the Transversity GPDs

Q^2=2.2 GeV^2, x_B=0.27

$\langle H_T \rangle$



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



- $\langle H_T \rangle^u$ 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.)
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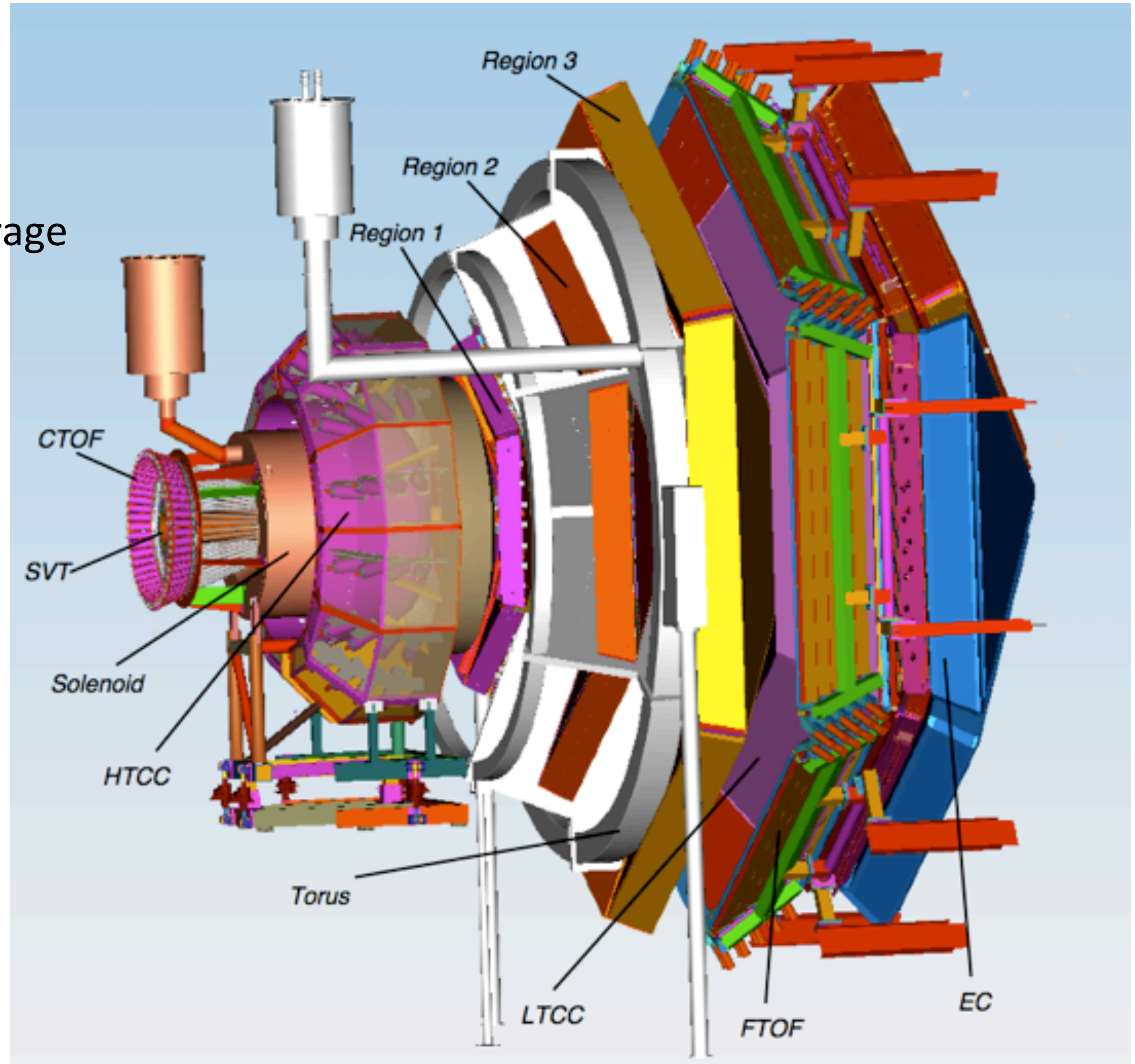
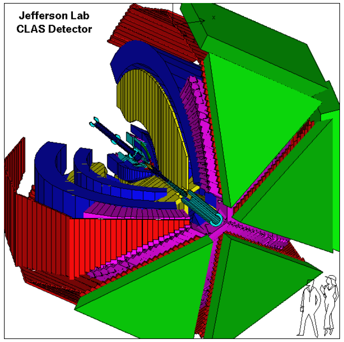
Jlab 12 GeV upgrade

CLAS12

- High luminosity
- Large acceptance
- Wide kinematic coverage
- High precision
- Improved particle ID



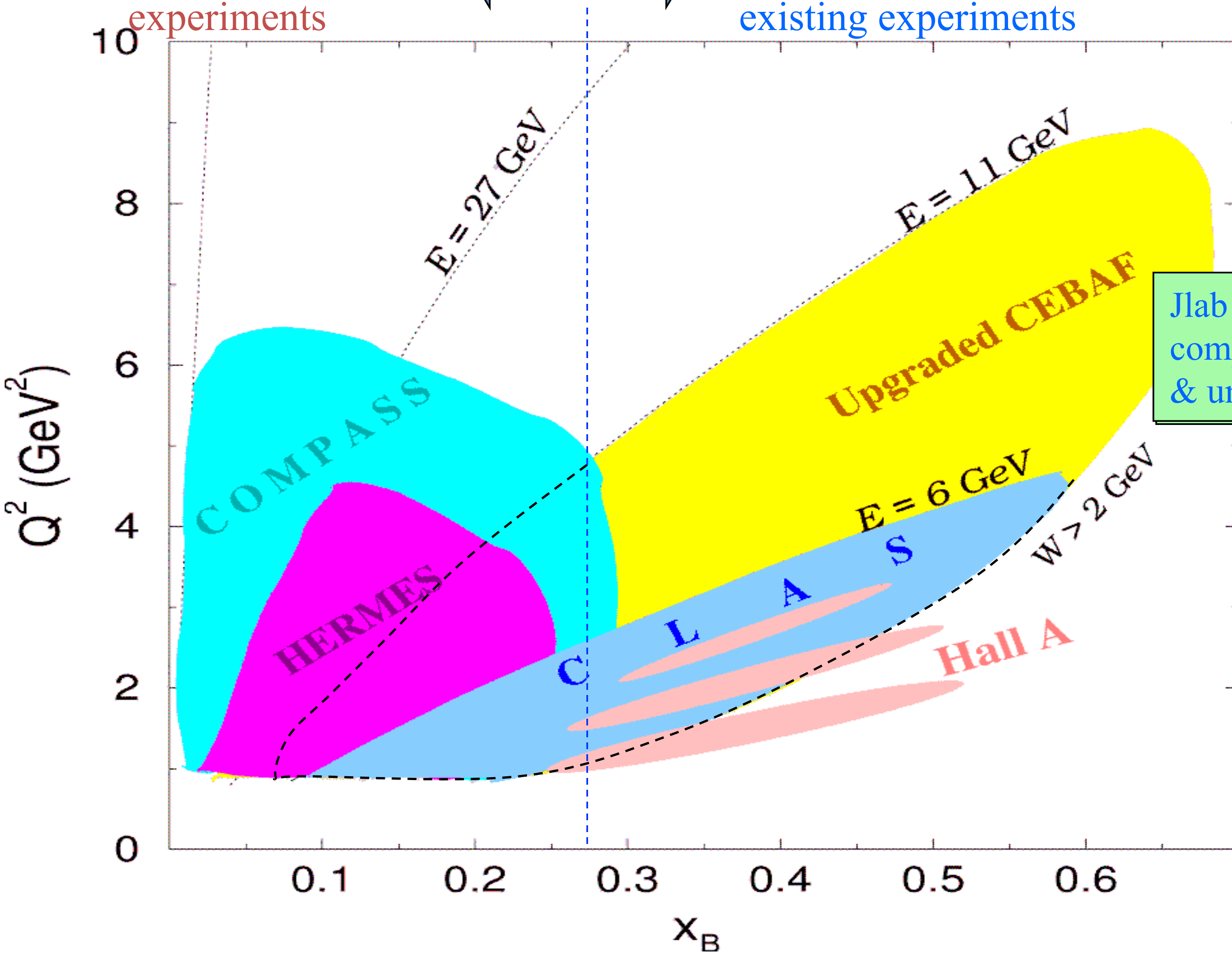
CLAS6



Kinematics coverage for deeply exclusive experiments

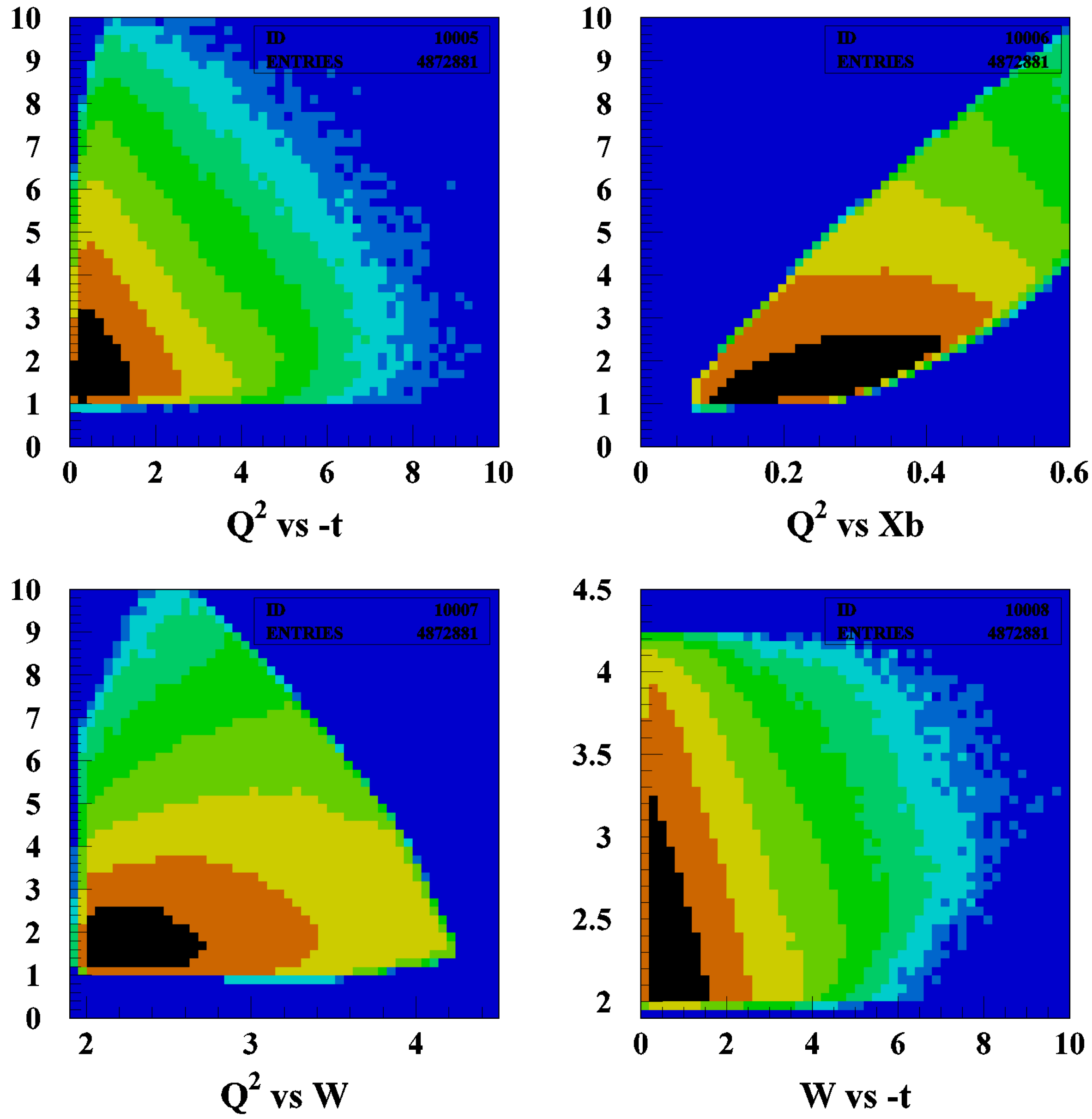
compete with other experiments

no overlap with other existing experiments

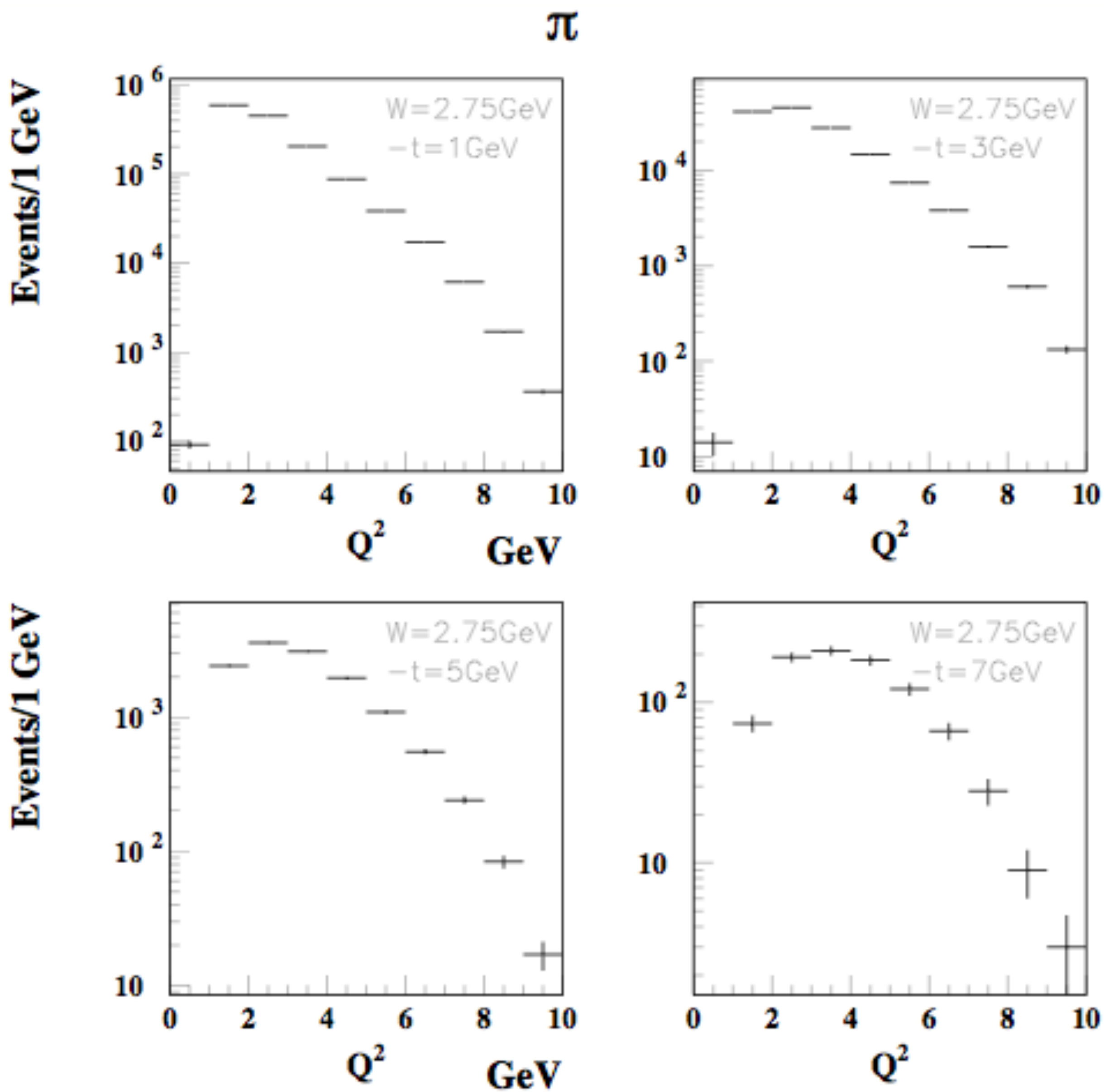


Jlab @ 12GeV complementary & unique

Kinematic Coverage at 11 GeV

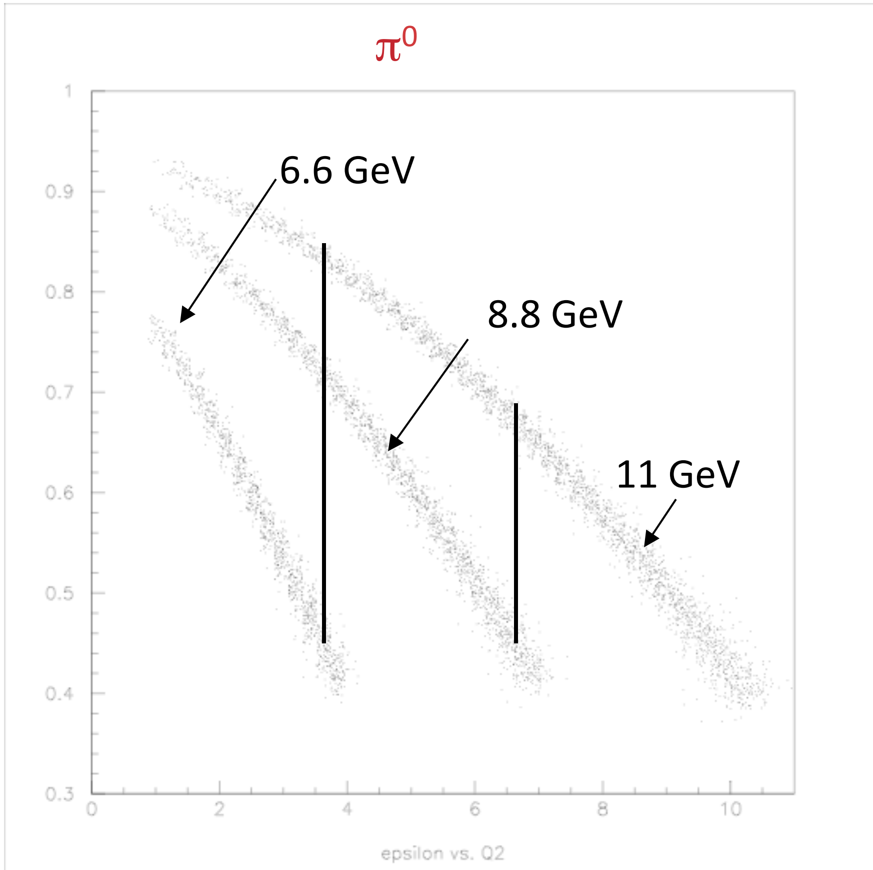


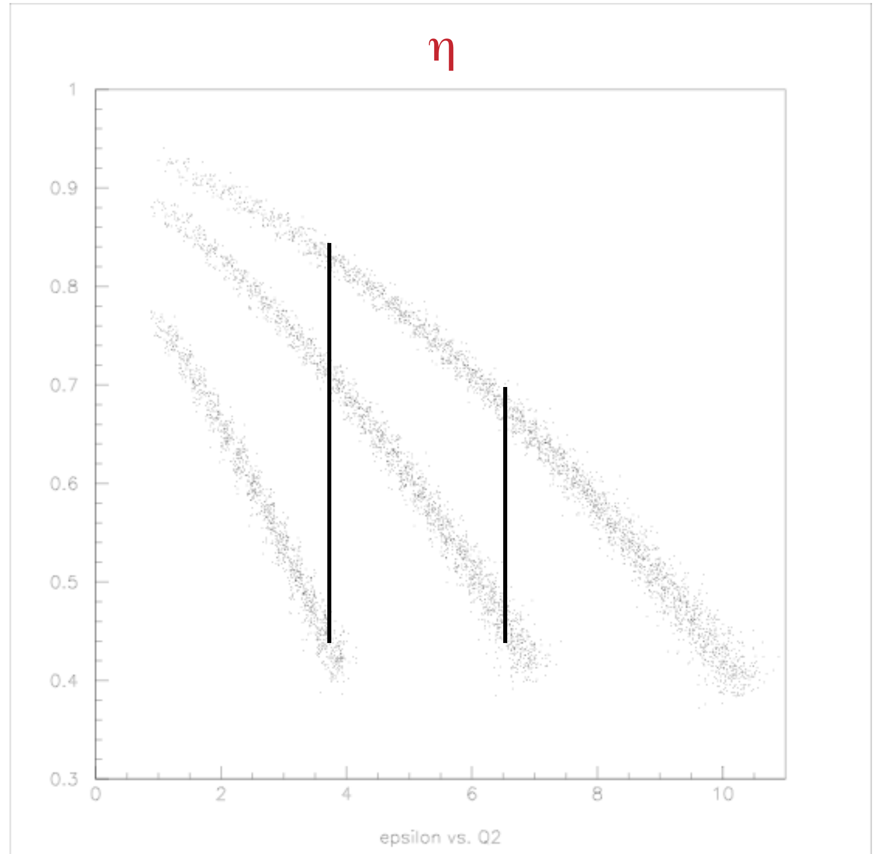
Statistics at W=2.75 GeV



Rosenbluth L/T Separation

ε vs Q^2



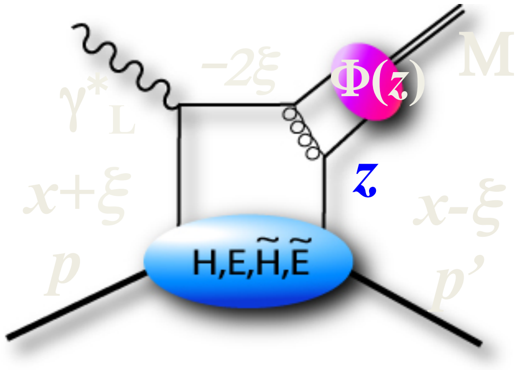


x_B=0.35 Δx_B=0.1

Summary

- CLAS π^0 and η data support the dominance of the transversity GPDs 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
- Exclusive electroproduction of π^0 and η mesons allows to extract generalized form factors $\langle H_T \rangle^{\pi,\eta}$ and $\langle \bar{E}_T \rangle^{\pi,\eta}$
- The combined π^0 and η data will provide the way for the flavor decomposition of the transversity GPDs
- CLAS12 will continue the GPD study with broader kinematics and higher statistics.

The End



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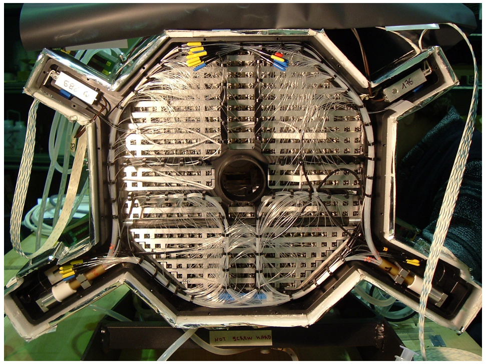

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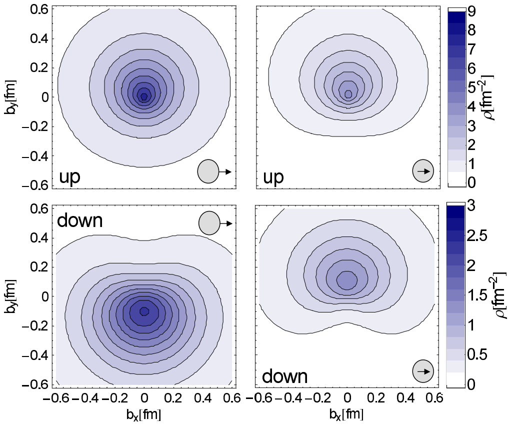

Generalized Form factors

- Generalized Form factors (extracted in the approximation of the transverse dominance) vs theoretical input to the model

- The comparison shows that the approximation is reasonable