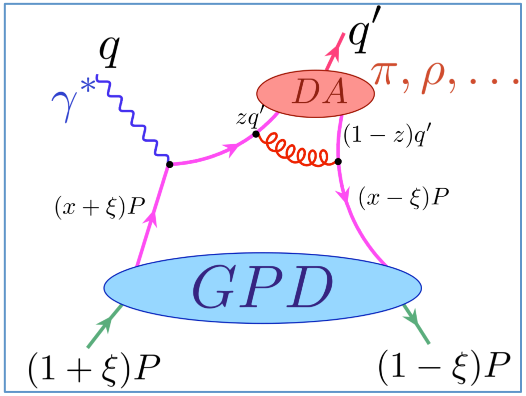
Transverse Spin Density of the Proton and Pseudoscalar Meson Electroproduction

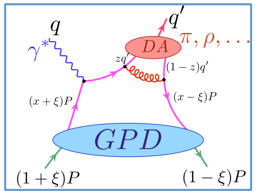
Valery Kubarovsky
Jefferson Lab

CLAS Collaboration Meeting,
July 13, 2018

Outline



- CLAS data on pseudoscalar meson electroproduction
- Transversity GPD and structure functions
- Flavor decomposition of the Transversity GPDs
- Impact Parameter Density for u and d-quarks
- Conclusion



$ep \to ep\pi^0$

Structure functions and GPDs

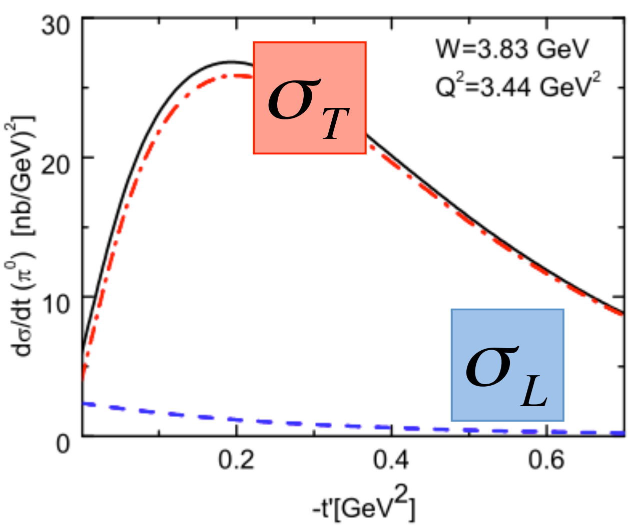
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}\left(\sigma_T + \epsilon\sigma_L + \epsilon\cos 2\phi_\pi \sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \sigma_{LT}\right)$$

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

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

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

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



<u>Transversity GPD model</u>

S. Goloskokov and P. Kroll

S. Liuti and G. Goldstein

- $\sigma_L << \sigma_T$

The brackets <F> denote the convolution of the elementary process with the GPD F (Generalized Form Factors, GFF)

π^0/η Exclusive Electroproduction with CLAS

PRL **109,** 112001 (2012) PHYSICAL REVIEW LETTERS week ending 14 SEPTEMBER 2012

Measurement of Exclusive π^0 Electroproduction Structure Functions and their Relationship to Transverse Generalized Parton Distributions

I. Bedlinskiy,[22] V. Kubarovsky,[35,30] S. Niccolai,[21] P. Stoler,[30] K. P. Adhikari,[29] M. Aghasyan,[18] M. J. Amaryan,[29] M. Anghinolfi,[19] H. Avakian,[35] H. Baghdasaryan,[39,41] J. Ball,[7] N. A. Baltzell,[1] M. Battaglieri,[19] R. P. Bennett,[29]

PHYSICAL REVIEW C **90**, 025205 (2014)

Exclusive π^0 electroproduction at $W > 2$ GeV with CLAS

I. Bedlinskiy,[19] V. Kubarovsky,[32,27] S. Niccolai,[18,12] P. Stoler,[27] K. P. Adhikari,[26] M. D. Anderson,[35] S. Anefalos Pereira,[15] H. Avakian,[32] J. Ball,[6] N. A. Baltzell,[1,31] M. Battaglieri,[16] V. Batourine,[32,21] A. S. Biselli,[9] S. Boiarinov,[32] J. Bono,[10]

PHYSICAL REVIEW C **95**, 035202 (2017)

Exclusive η electroproduction at $W > 2$ GeV with CLAS and transversity generalized parton distributions

I. Bedlinskiy,[22] V. Kubarovsky,[36,31] P. Stoler,[31] K. P. Adhikari,[25] Z. Akbar,[12] S. Anefalos Pereira,[17] H. Avakian,[36] J. Ball,[7] N. A. Baltzell,[36,34] M. Battaglieri,[18] V. Batourine,[36,24] A. S. Biselli,[10,5] S. Boiarinov,[36] W. J. Briscoe,[14] V. D. Burkert,[36]

PRL 109, 112001 (2012) PHYSICAL REVIEW LETTERS week ending 14 SEPTEMBER 2012

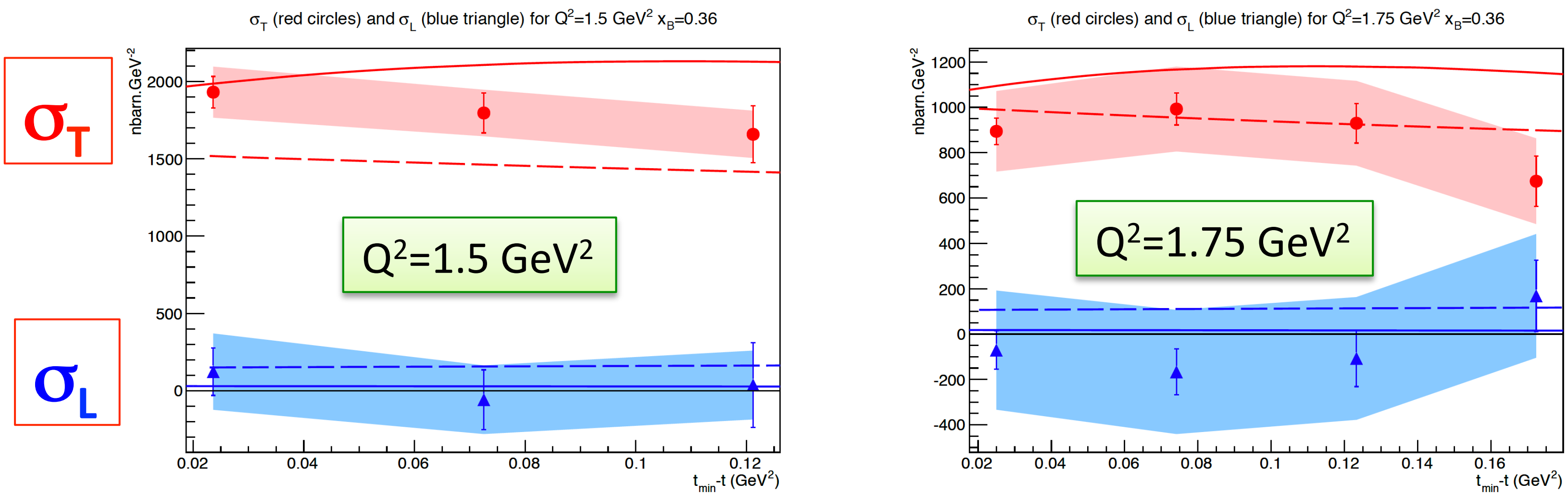
Measurement of Exclusive π^0 Electroproduction Structure Functions and their Relationship to Transverse Generalized Parton Distributions

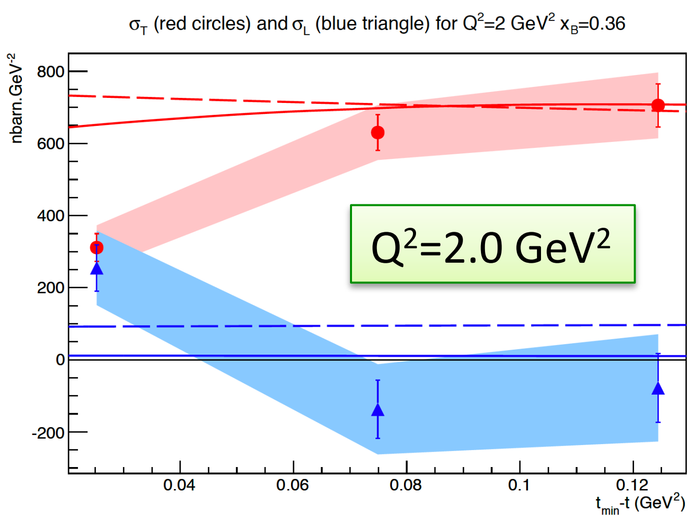
I. Bedlinskiy,[22] V. Kubarovsky,[35,30] S. Niccolai,[21] P. Stoler,[30] K. P. Adhikari,[29] M. Aghasyan,[18] M. J. Amaryan,[29]

- The measured cross section of π^0 electroproduction is much larger than expected from leading-twist handbag calculation. This means that the contribution of the longitudinal cross section σ_L is small in comparison with σ_T. The same conclusion can be made in a almost model independent way from the comparison of the cross sections σ_U, σ_{TT} and σ_{LT}.

- The data appear to confirm the expectation that pseudoscalar and, in particular, π^0 electroproduction is a uniquely sensitive process to access the transversity GPDs $\bar{E}_T$ and H_T.

Rosenbluth separation σ_T and σ_L
Hall-A Jefferson Lab



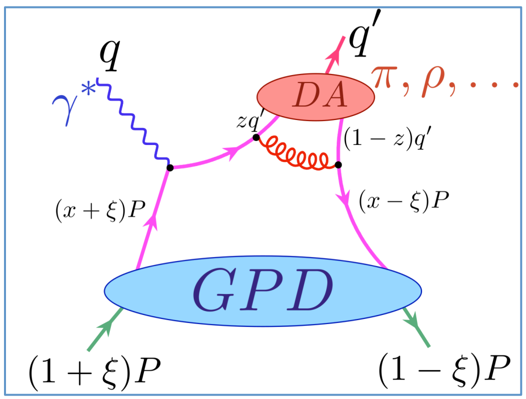


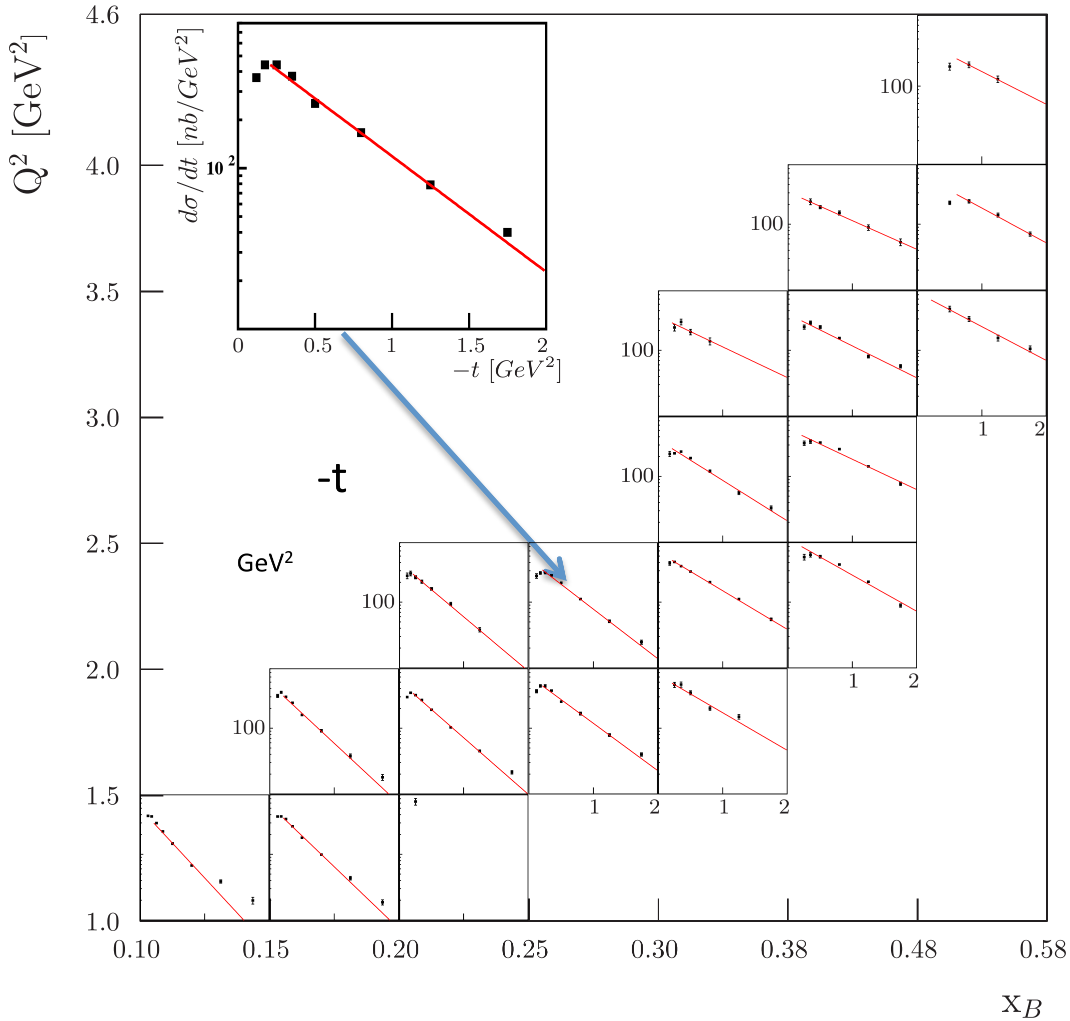
- Experimental **proof** that the transverse π^0 cross section is dominant!
- It opens the direct way to study the transversity GPDs in pseudoscalar exclusive production

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

$d\sigma_U/dt$

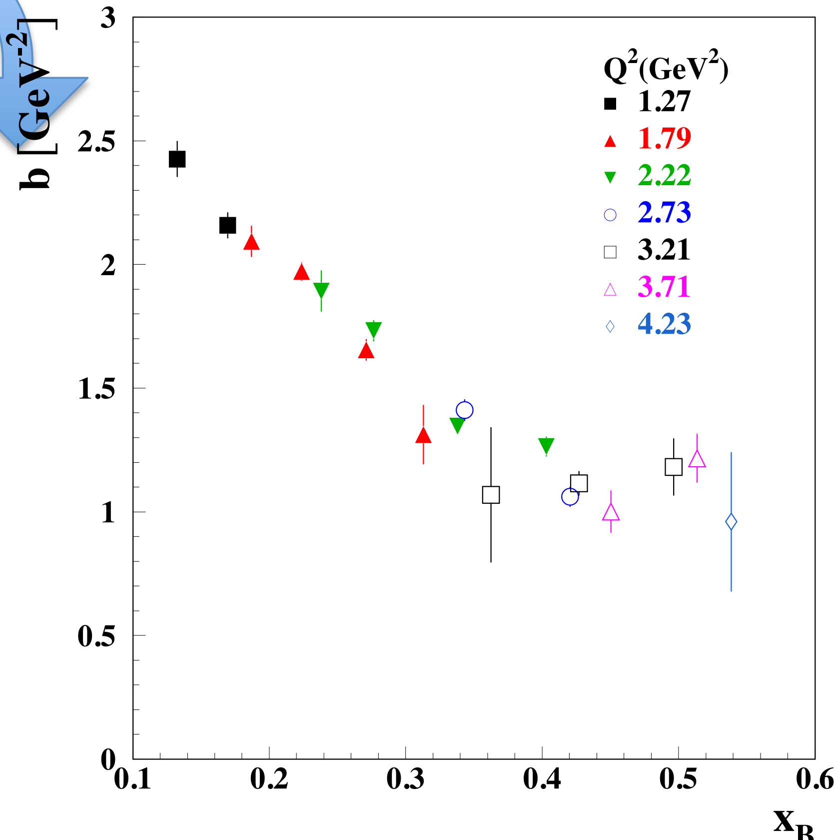
$$\frac{d\sigma}{dt}(\gamma^* p \rightarrow ep\pi^0) \propto e^{bt}$$





t-slope parameter: x_B dependence

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

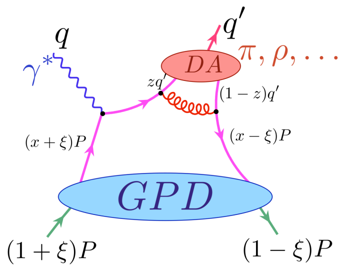


The slope parameter is decreasing with increasing x_B. The Q^2 dependence is weak. Looking to this picture we can say that the perp width of the partons with $x \rightarrow 1$ goes to zero.

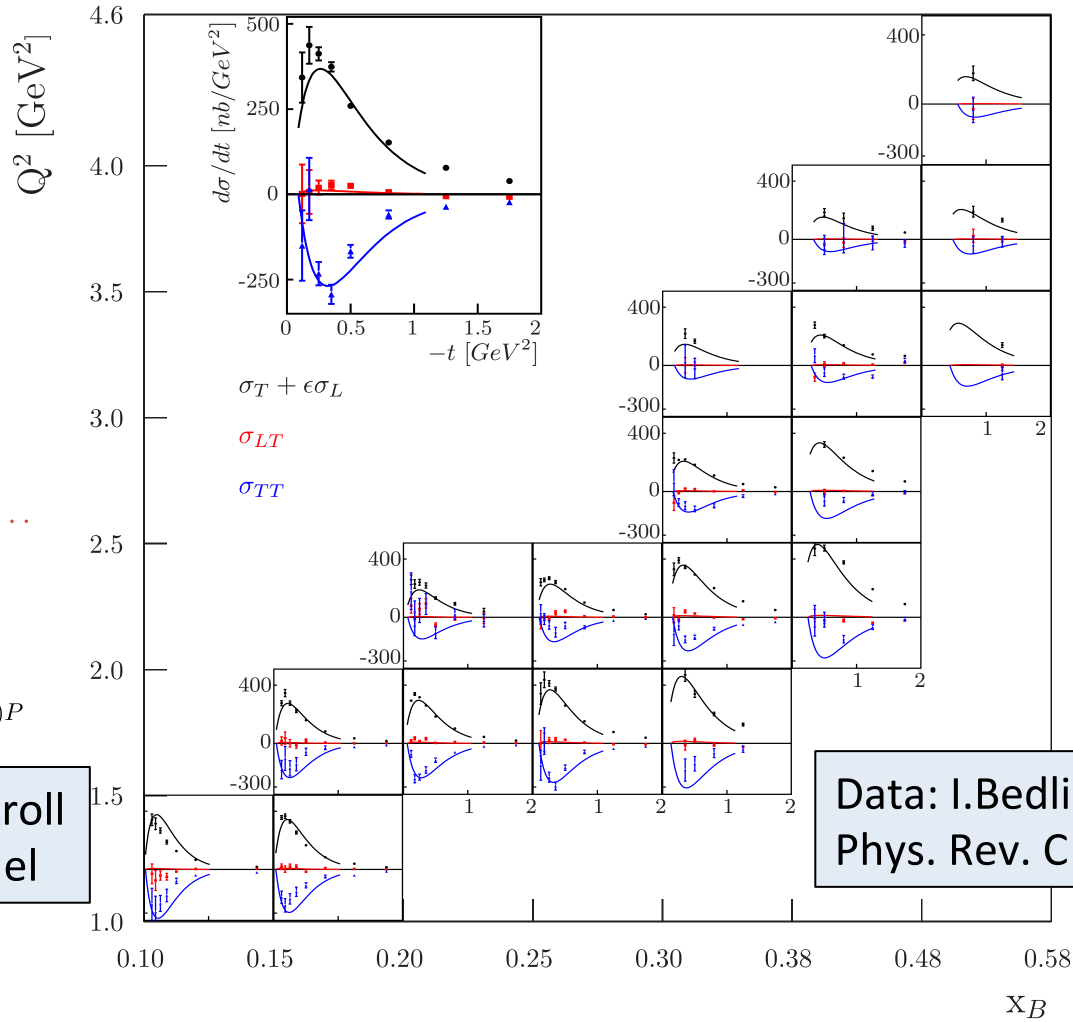
Structure Functions

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

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



Curves: Goloskokov, Kroll
Transversity GPD model

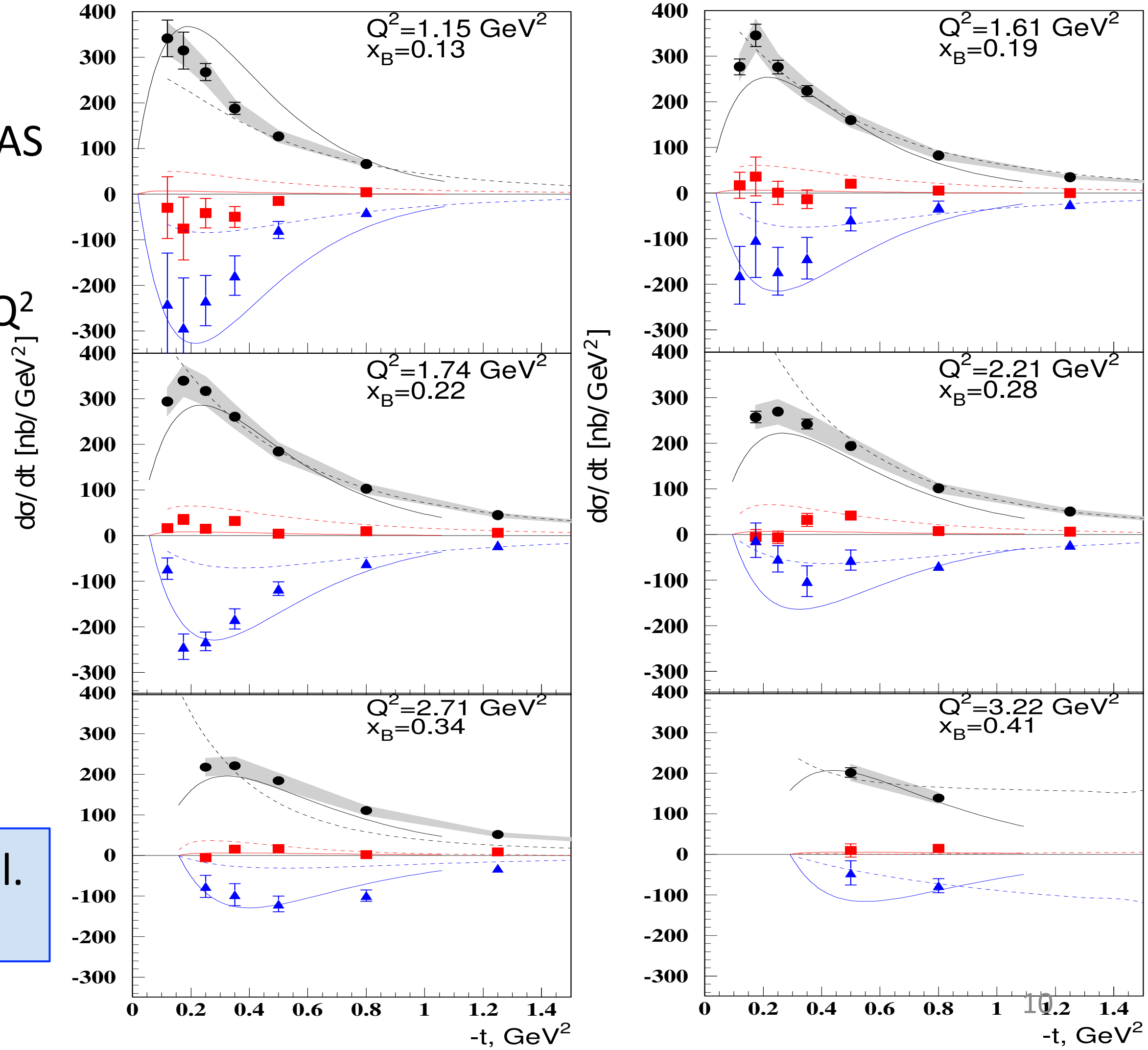


Data: I.Bedlinskiy et al. (CLAS)
Phys. Rev. C 90, 039901 (2014)

CLAS data and GPD theory predictions

- ***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.

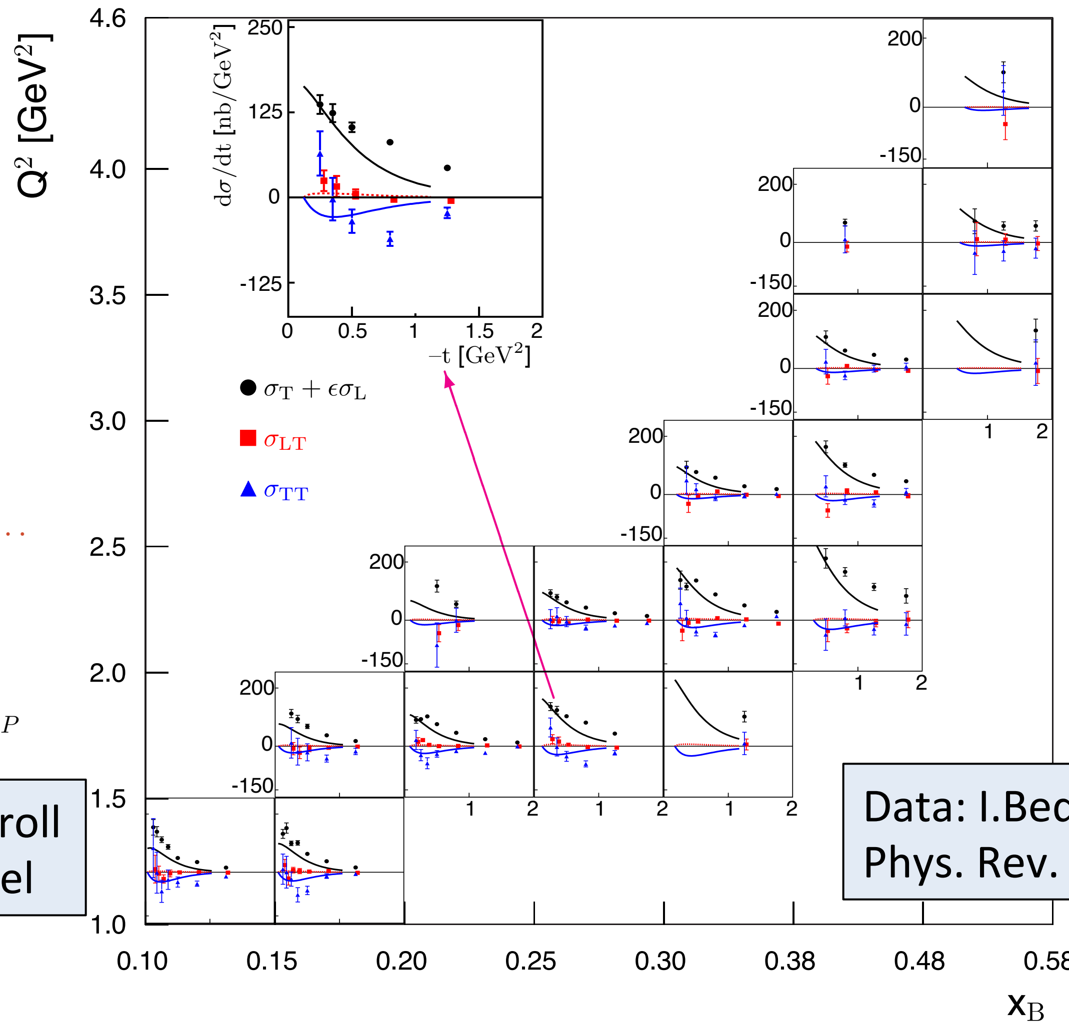
Solid: S. Goloskokov and P. Kroll
Dots: S. Liuti and G. Goldstein

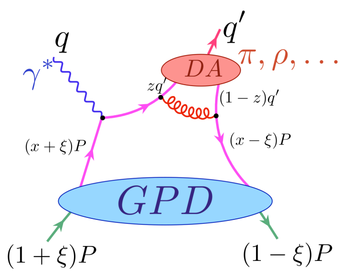


CLAS collaboration. I Bedlinskiy et al. Phys.Rev.Lett. 109 (2012) 112001

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

$\gamma^* p \rightarrow p\eta$

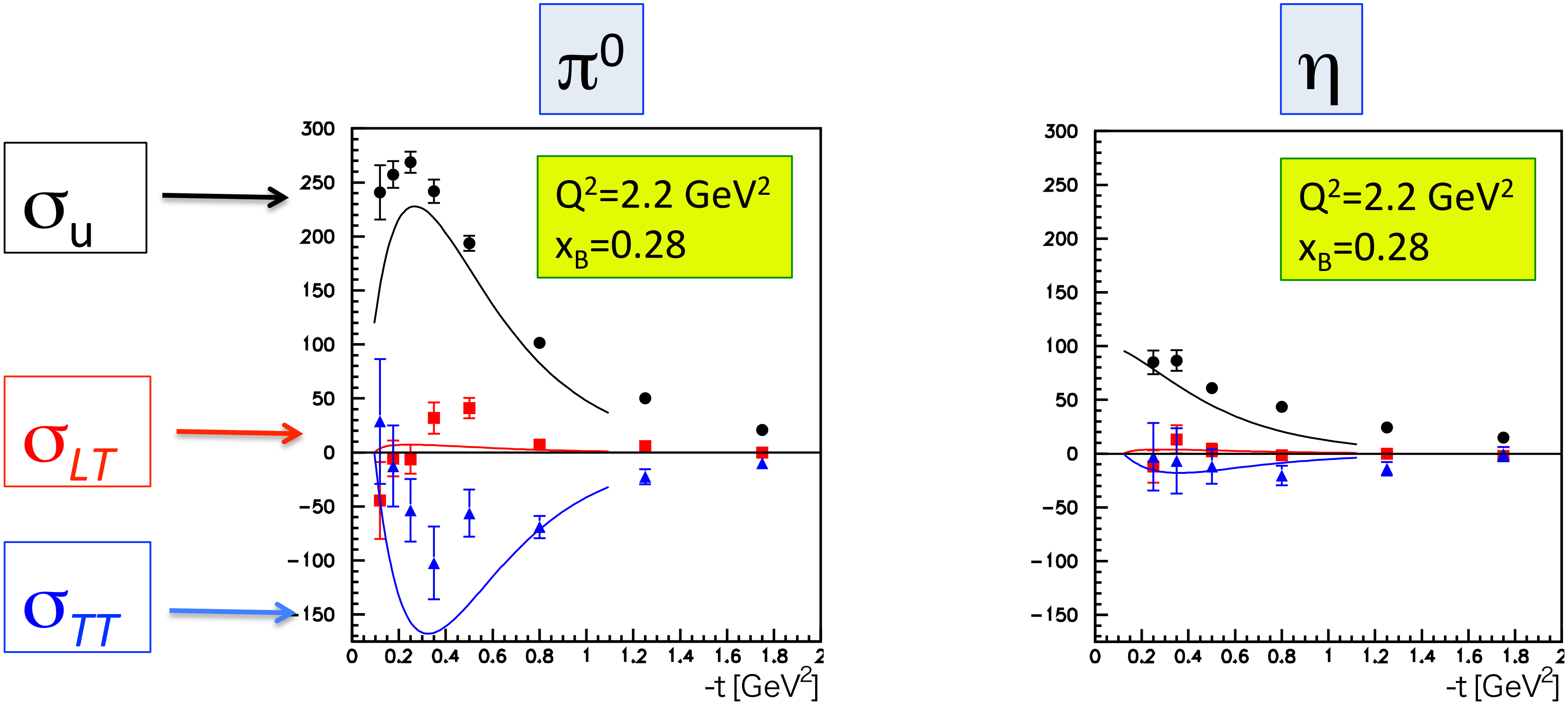




Curves: Goloskokov, Kroll
Transversity GPD model

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

Comparison π^0/η



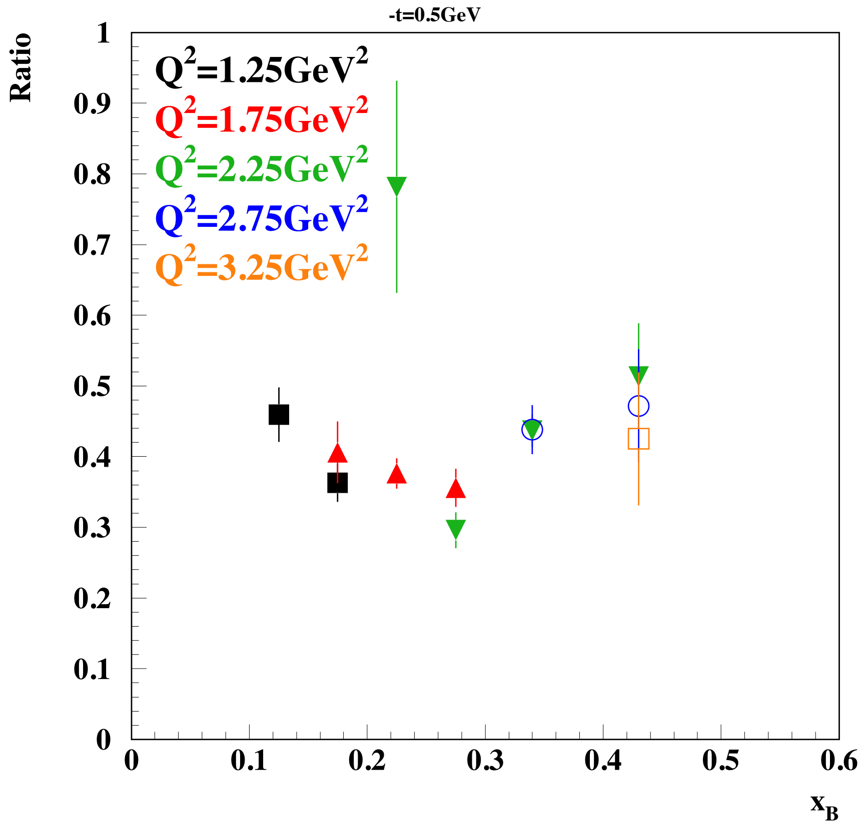
CLAS-Phys.Rev.C95(2017)

- $\sigma_U = \sigma_T + \varepsilon\sigma_L$ 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

η/π^0 ratio

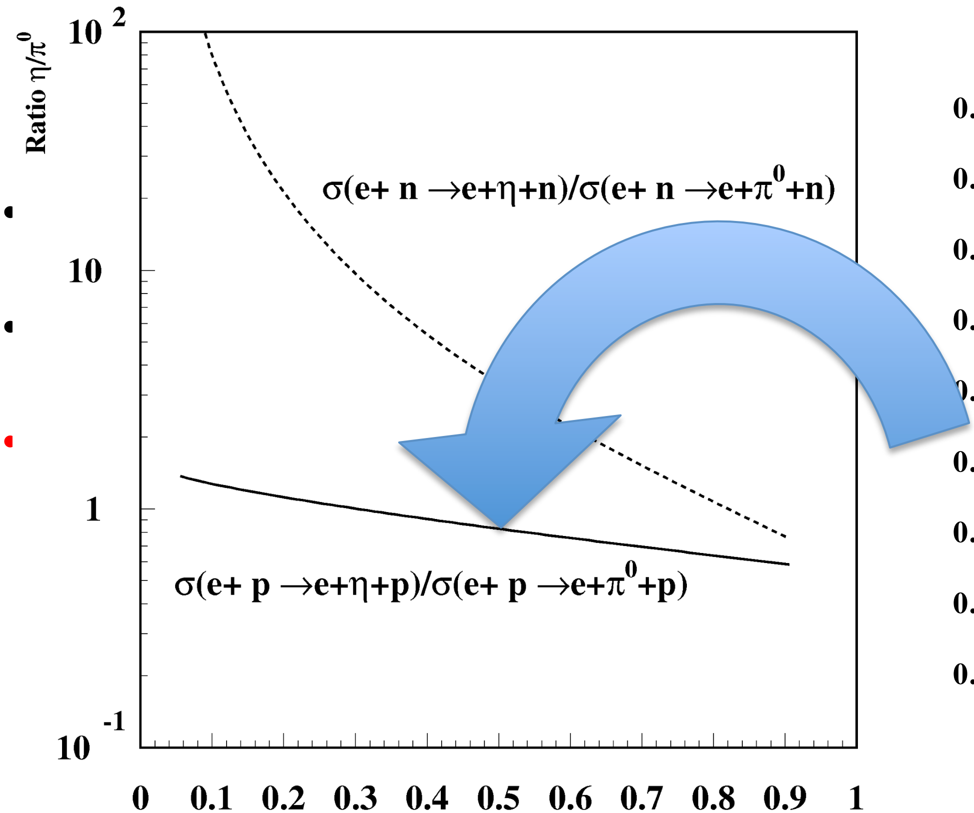
$$\frac{\sigma(ep \to ep\eta)}{\sigma(ep \to ep\pi^0)}$$

- 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).

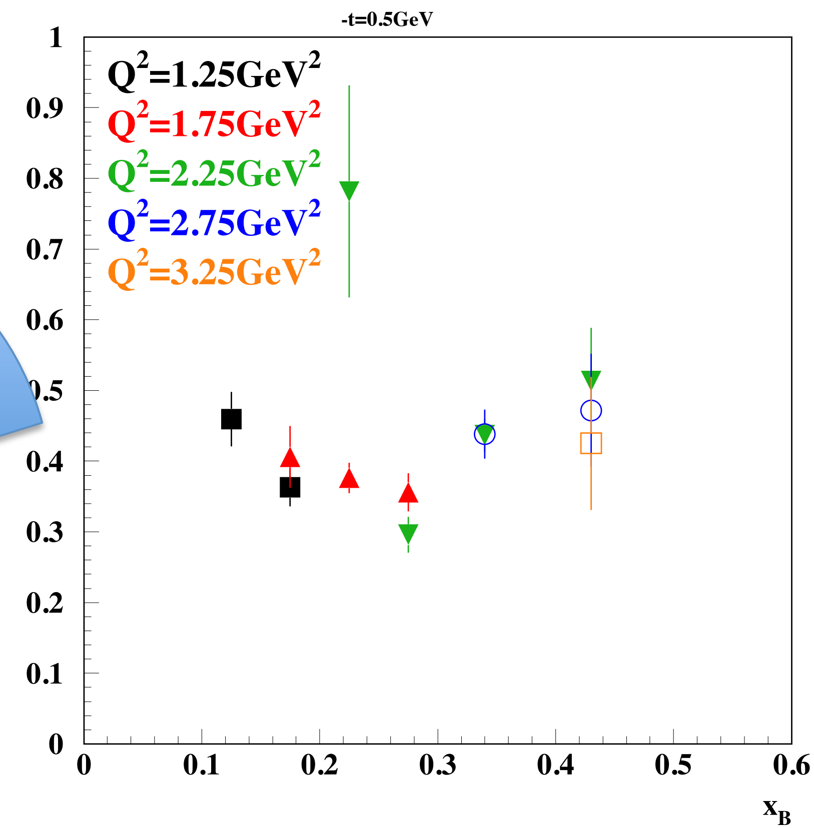


η/π^0 ratio

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



Theoretical prediction R=1 for the Chiral-even GPD models ($\sigma_L >> \sigma_T$)
F, Frankfurt et al,Phys.Rev D59,1999

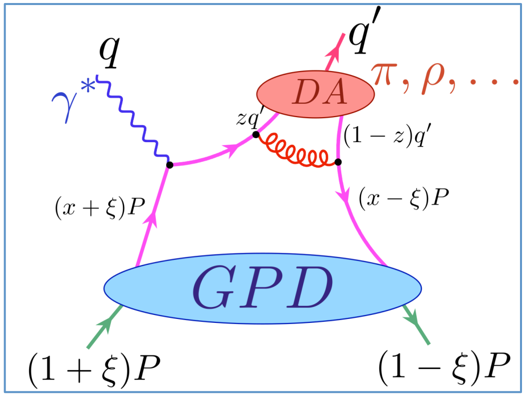


CLAS-Phys.Rev.C95(2017)

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

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

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

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

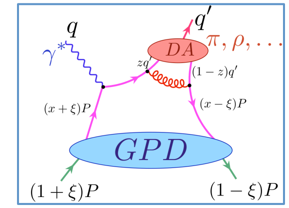
$$\langle \bar{E}_T\rangle = \Sigma_\lambda \int_{-1}^{1} dx M(x,\xi,Q^2,\lambda) \bar{E}_T(x,\xi,t)$$

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

- *In the approximation* of the transversity GPDs dominance, that is supported by Jlab data, $\sigma_L << \sigma_T$, we have direct access to the generalized form factors for π and η production.

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

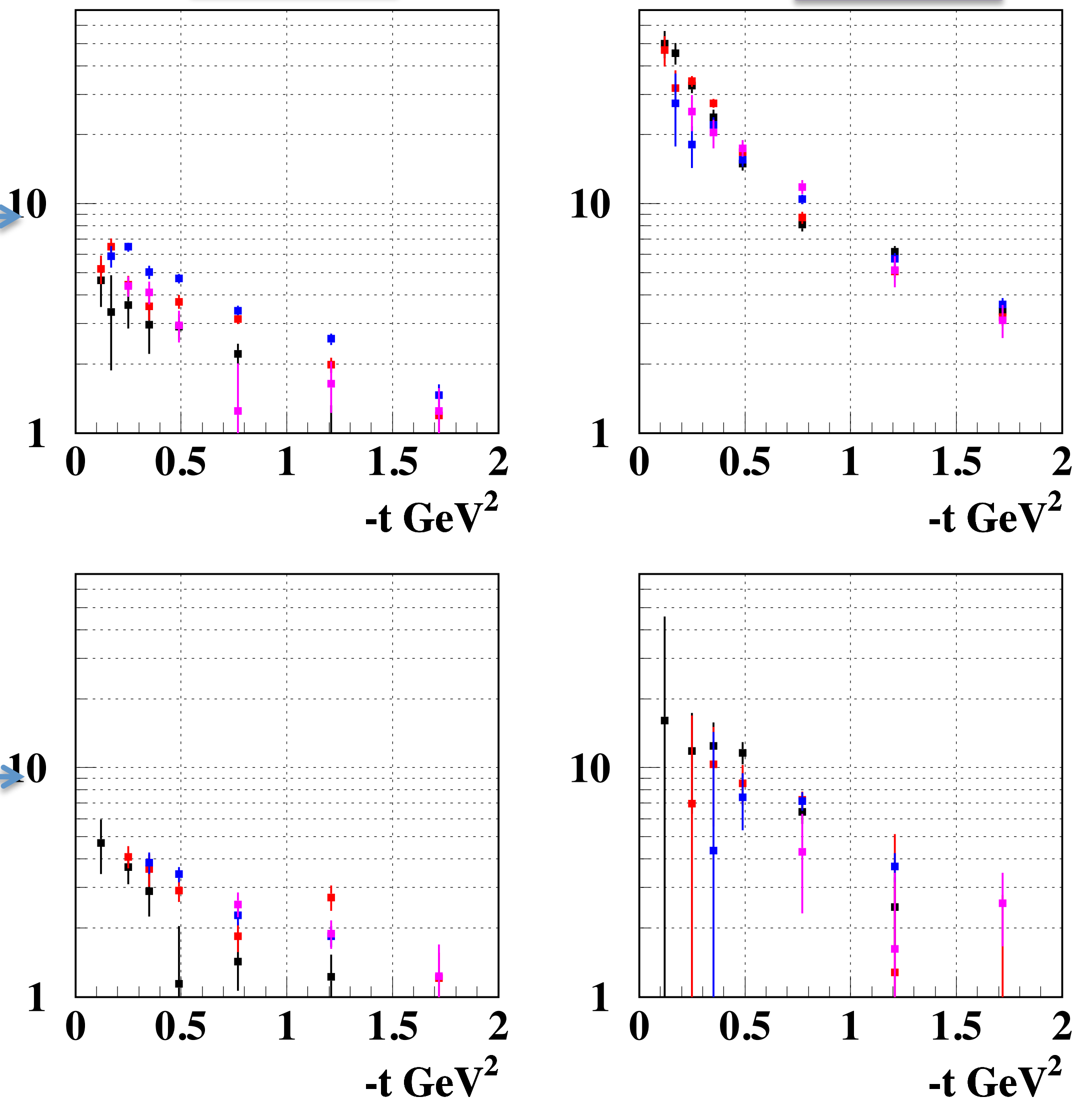
Generalized Form factors



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

π^0

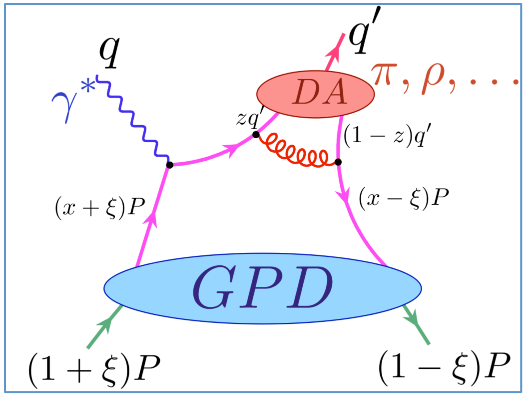
η

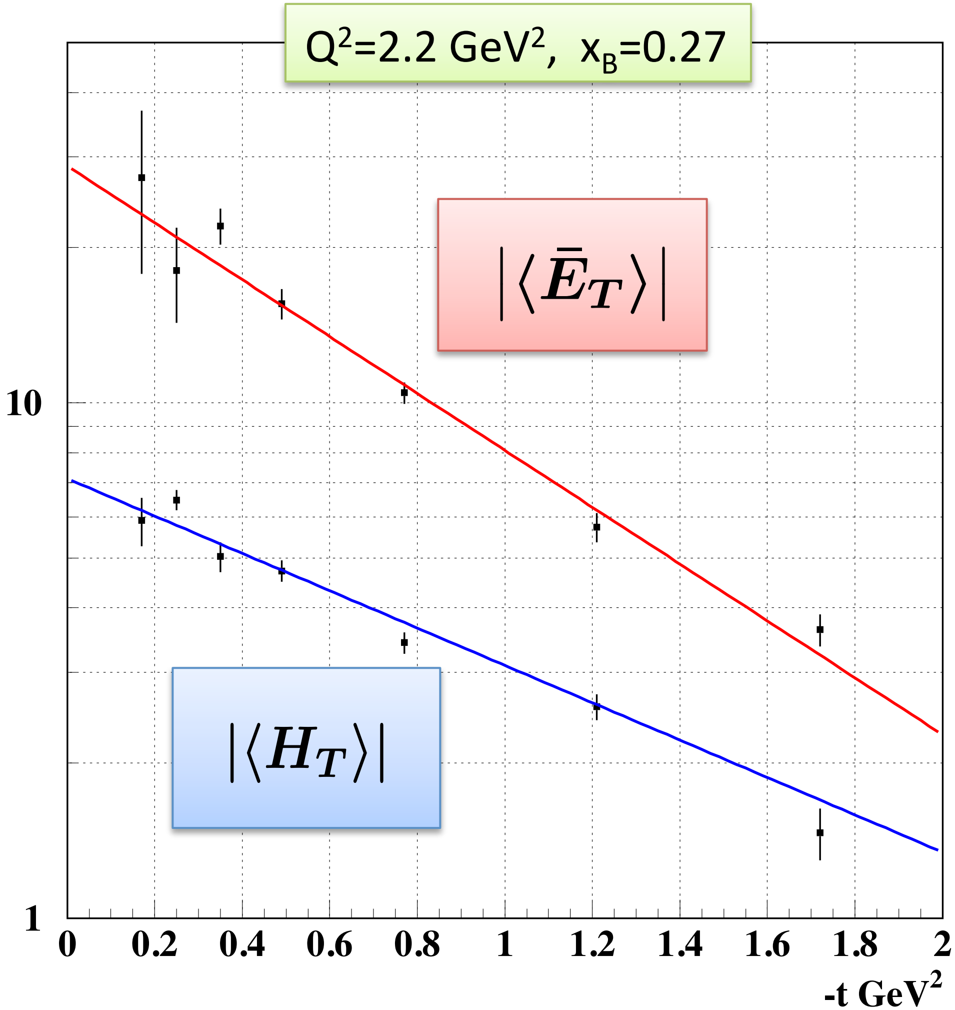


Q^2 GeV^2	x_B
1.2	0.15
1.8	0.22
2.2	0.27
2.7	0.34

- $\bar{E}_T$ > 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

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

VK, arXiv:1601.04367

GPD Flavor Decomposition

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

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

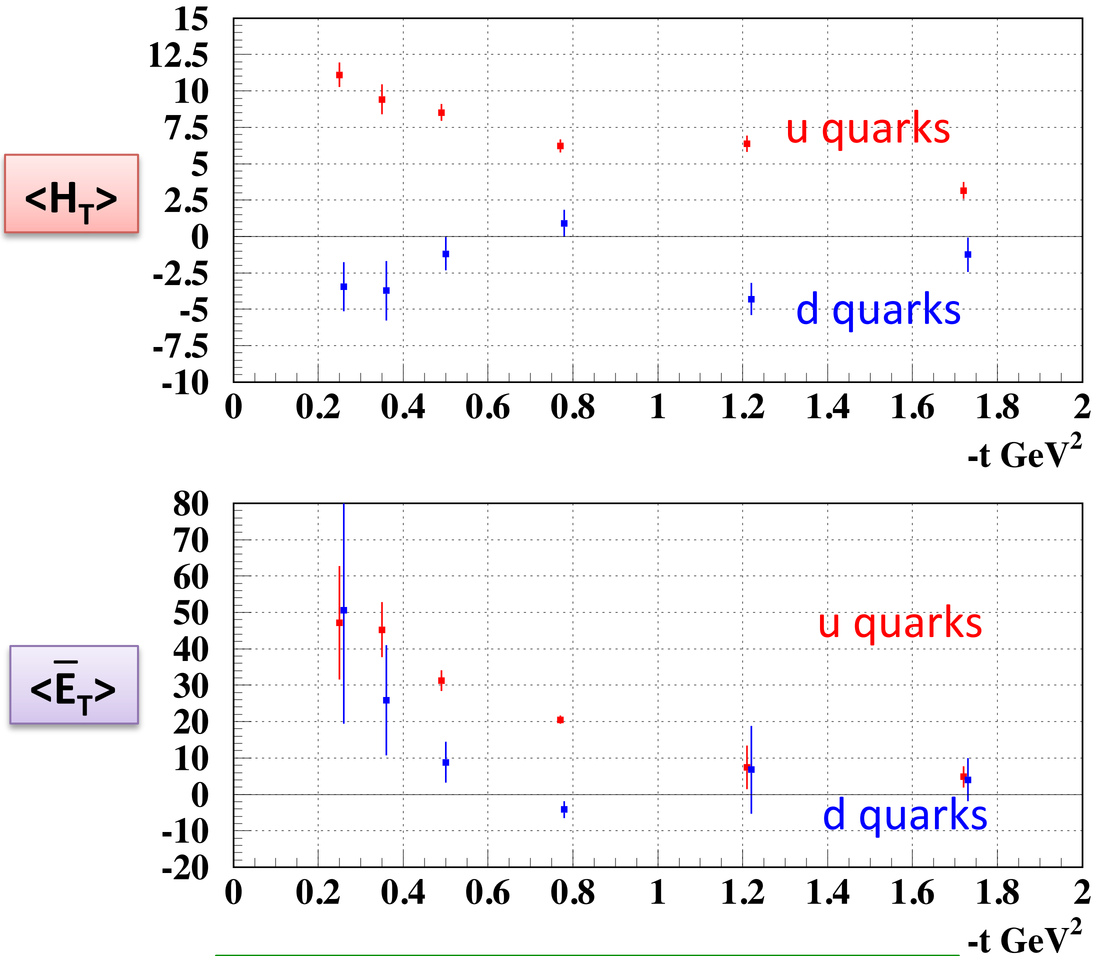
$$H_T^{u} = \frac{3}{2\sqrt{2}}[H_T^{\pi} + \sqrt{3}H_T^{\eta}]$$

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

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 assumption that the relative phase between u and d is 0 or 180 degrees. This assumption confirmed at least for $\bar{E}_T$

Flavor Decomposition of the Transversity GPDs



VK arXiv: 1601.04367 [hep-ex] 2016

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

- <H_T>^{u} and <H_T>^{d} have different signs for u and d-quarks in accordance with the transversity function h_1 (Anselmino et al.)
- <$\bar{E}_T$>^{d} and <$\bar{E}_T$>^{u} seem to have the same signs
- Decisions shown with positive values of u-quark's GPDs only

From GFF to GPD

- The access to GPDs through DVMP is indirect because cross section depends on Generalized Form Factors (GFFs), i.e. convolution of GPDs with sub processes.
- GFFs (or CFF in DVCS) form factors are an intermediate step towards GPD extraction
- The way to go is the global fit of experimental observables using GPD models with parameters. It may include DVCS and DVMP experimental data set.
- The DVCS community made an impressive steps in this direction. We can do similar attempts for the transversity GPDs.
- There are several models on the market that provide such a parameterization (PK,SL,SG,GG,CW…)
- The Jlab pseudoscalar electroproduction data(cross section on different targets, asymmetries etc) gives the unique opportunity to access the critical parameters of the transversity GPDs.

The Fourier Transform of Generalized Parton Distribution

- The Fourier transforms of GPDs at ξ = 0 describe the distribution of partons in the transverse plane (M. Burkardt, 2002)
- It was shown that they satisfy positivity constraints which justify their physical interpretation as a probability density
- **H** is related to the impact parameter distribution of unpolarized quarks for an unpolarized nucleon
- **$\tilde{H}$** is related to the distribution of longitudinally polarized quarks in a longitudinally polarized nucleon
- **E** is related to the distortion of the unpolarized quark distribution in the transverse plane when the nucleon has transverse polarization.
- **$\bar{E}$** is related to the distortion of the polarized quark distribution in the transverse plane for an unpolarized nucleon

$$\mathcal{K}(x,\vec{b}) = \int \frac{d^2\vec{\Delta}}{(2\pi)^2} \exp^{-i\vec{b}\cdot\vec{\Delta}} K(x,t=-\Delta^2)$$

GPD Parameterization and Fourier Transform

$$\mathcal{K}(x,\vec{b}) = \int \frac{d^2\vec{\Delta}}{(2\pi)^2} \exp^{-i\vec{b}\cdot\vec{\Delta}} K(x, t = -\Delta^2)$$

GPD Parameterization (Diehl, Kroll 2013)

$$K(x,t) = k(x) \cdot \exp^{t \cdot f(x)}$$

forward limit k(x) and the profile function f(x)

$$\mathcal{K}(x,\vec{b}) = \frac{1}{4\pi} \frac{k(x)}{f(x)} \exp^{-b^2/4f(x)}$$

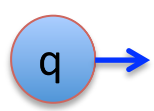
$$f(x) = (B + \alpha' \ln 1/x) \cdot (1-x)^3 + A \cdot x \cdot (1-x)^2$$

A,B,α’ are the model parameters

The Density of Transversely Polarized Quarks (in x-direction) in an Unpolarized Proton

$\bar{E}$ is related to the distortion of the polarized quark distribution in the transverse plane for an unpolarized nucleon

$$\delta(x,\vec{b}) = \frac{1}{2}[H(x,\vec{b}) - \frac{b_y}{m}\frac{\partial}{\partial b^2}\bar{E}_T(x,\vec{b})]$$



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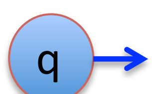
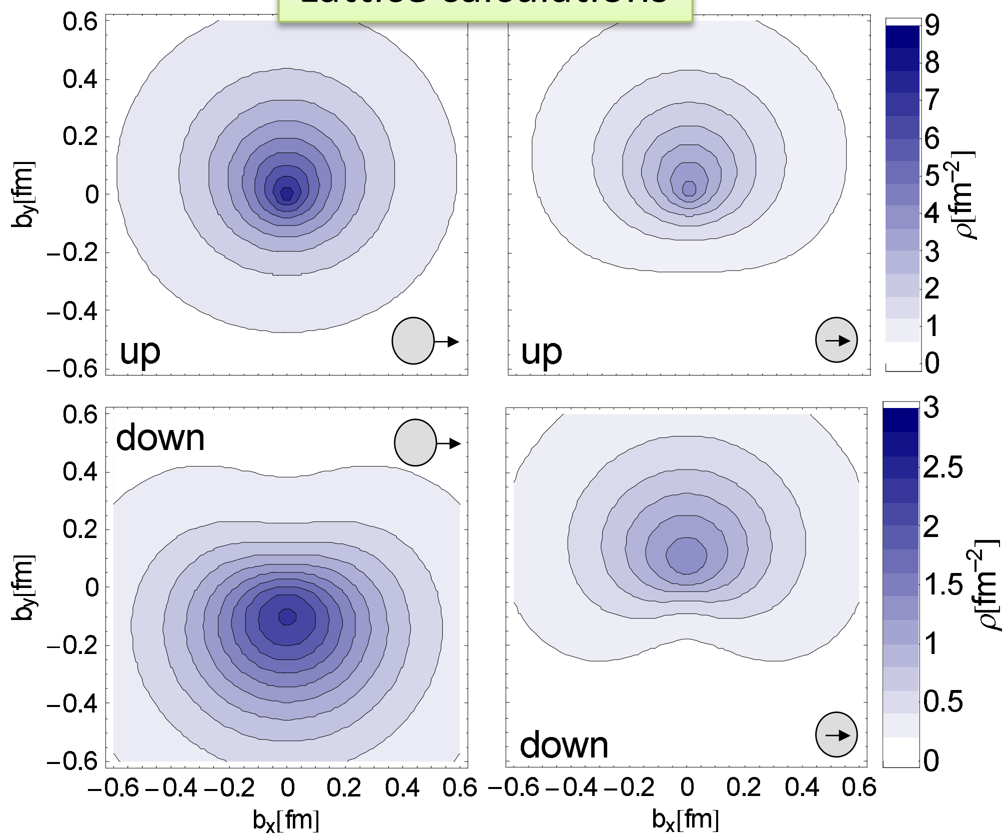


Integrated Over x Transverse Densities for u and d Quarks in the Proton

Lattice calculations

Strong distortions for unpolarized quarks in transversely polarized proton



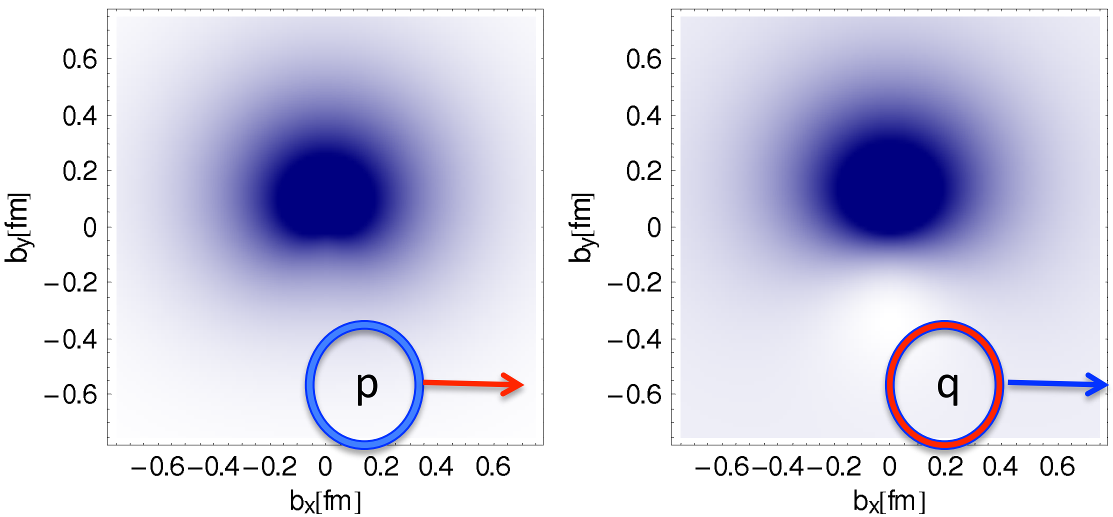
Strong distortions for transversely polarized quarks in an unpolarized proton

Controlled by E

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

Gockeler et al, Phys. Rev. Lett. 98, 222001 (2007), lattice

GPD model: integrated over *x* Impact Parameter Density for u-quarks



- **Left:** unpolarized u-quarks in a proton with transverse spin vector.
- **Right**: the distribution of u-quarks with transverse spin vector in an unpolarized proton.

M. Diehl and Ph Hagler (2005) GPD model with "some reasonable " parameters.

CLAS data and Proton Spin Density Distributions for u and quarks

- CLAS data on π^0/η electroproduction gives direct access to the Etbar GPD

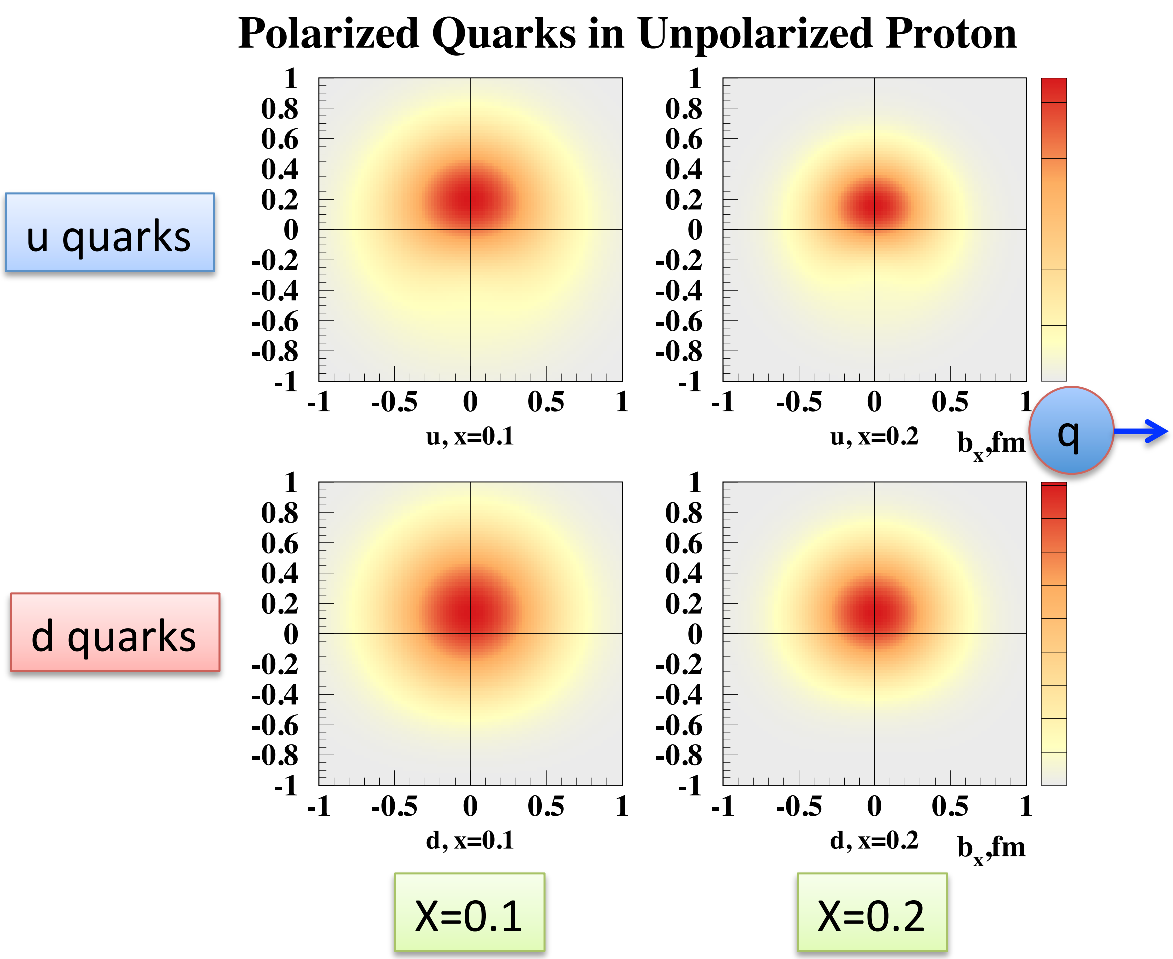
$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_P^2}{Q^8}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle \bar{E}_T\rangle\right|^2\right]$$

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

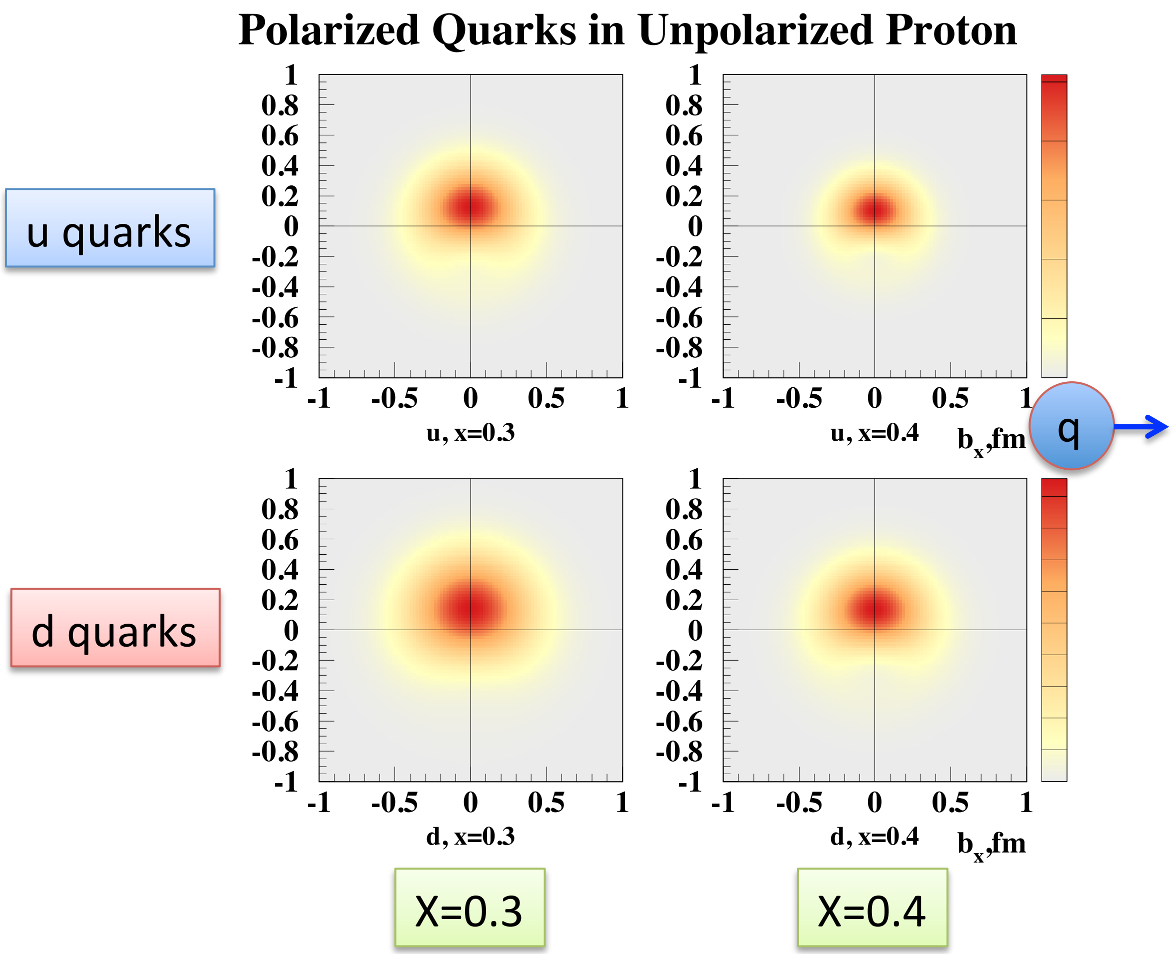
- GPD model successfully described our data
- The spin density of the proton was extracted using the Kroll's model
- We can map the u and d –quarks spin density distributions as a function of x

M. Diehl and P. Kroll, Eur. Phys. J. C 73, no. 4, 2397 (2013)

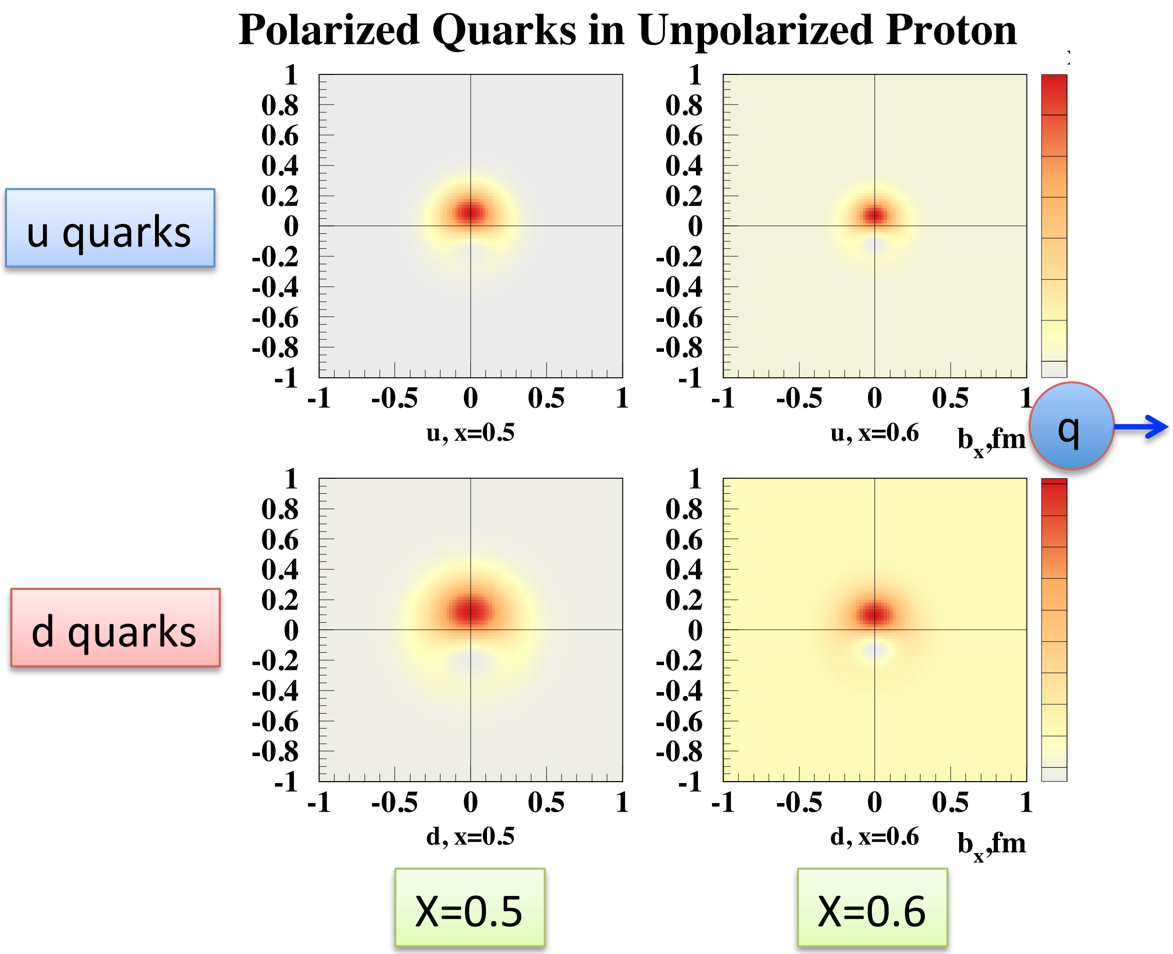
Transverse Densities for u and d Quarks in the Proton



Transverse Densities for u and d Quarks in the Proton



Transverse Densities for u and d Quarks in the Proton



Future developments

- CLAS12 took data this year with proton target and will continue taking data in the same configuration in August. Next in a queue – deuteron target.

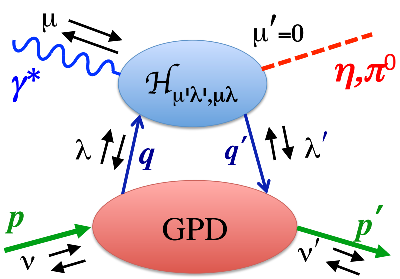
- Cross sections:
  - $ep \to ep(\pi^0, \eta)$
  - $en \to en(\pi^0, \eta)$
  - $ep \to e\pi^+ n$
  - $ep \to eK^+ \Lambda$

- Asymmetries:
  - A_{LU} – beam spin
  - A_{UL} – target spin
  - A_{LL} – beam target

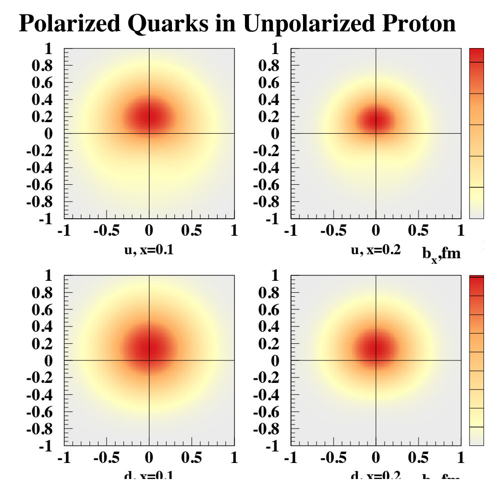
Summary

- Jlab 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 combined π^0 and η, proton and neutron data will provide the way for the flavor decomposition of transversity GPD
- The density distributions of the polarized u and d quarks in an unpolarized proton were extracted with the GPD model parameters that describes CLAS π^0 and η data
- The measurement of deeply virtual exclusive pseudoscalar meson production uniquely measures transversity GPDs, and has already begun to access their underlying polarization distributions of quarks in the nucleon. The new CLAS12 experiments are a major component of the CLAS12 program to provide detailed tomographic images the quark and gluon distributions.

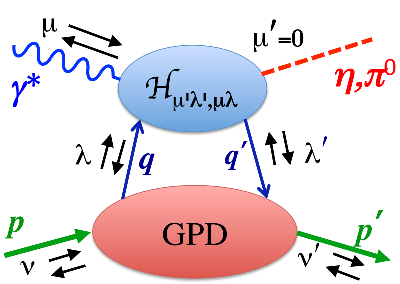
The End


μ
μ′=0
γ*
η,π0
GPD
λ
q
q′
λ′
p
p′
ν
ν′

+ clas =


Polarized Quarks in Unpolarized Proton
u, x=0.1
u, x=0.2
b_x,fm

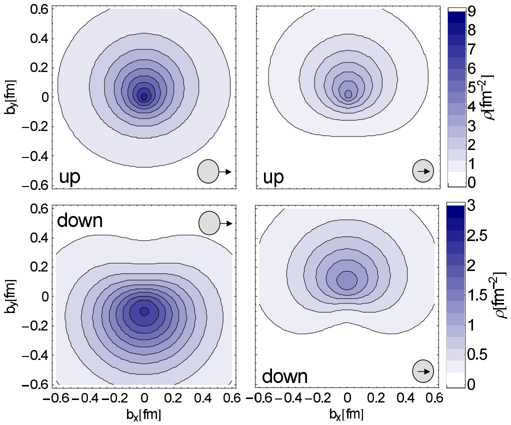
The End


μ
μ′=0
γ*
η,π0
$\mathcal{H}_{\mu'\lambda',\mu\lambda}$
λ
q
q′
λ′
p
GPD
p′
ν
ν′

+

clas

=


up
up
down
down
b_y[fm]
b_x[fm]
ρ[fm^-2]