Studies of Transversity GPDs in Exclusive Reactions

Valery Kubarovsky

Jefferson Lab, USA

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U.S. DEPARTMENT OF ENERGY
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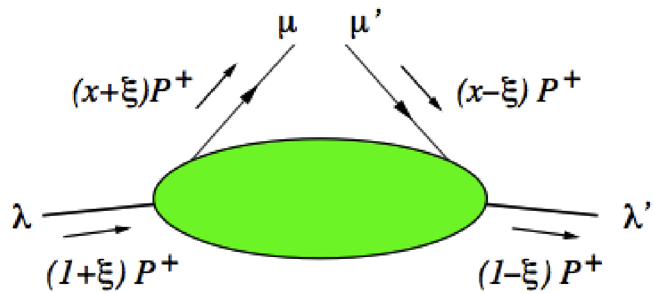
clas

Outlook

- Current understanding of transversity GPDs
- Accessing transversity GPDs through pseudoscalar meson electroproduction
- Review of existing experimental data
- Extraction of transversity GPD parameters through global fits base on the GK model
- CLAS12: Status of data taking and analysis
- Conclusion

Generalized Parton Distributions



- A wealth of information on the nucleon structure is encoded in GPDs.
- GPDs are the functions of three kinematic variables: x, ξ and t
- They admit a particularly intuitive physical interpretation at zero skewness $\xi=0$, where after a Fourie transform GPDs describe the spatial distribution of quarks with given longitudinal momentum in the transverse plane.

In the quark sector

- 4 chiral even GPDs where partons do not flip helicity

$$H^q, \tilde{H}^q, E^q, \tilde{E}^q$$

- 4 chiral odd GPDs which flip the parton helicity

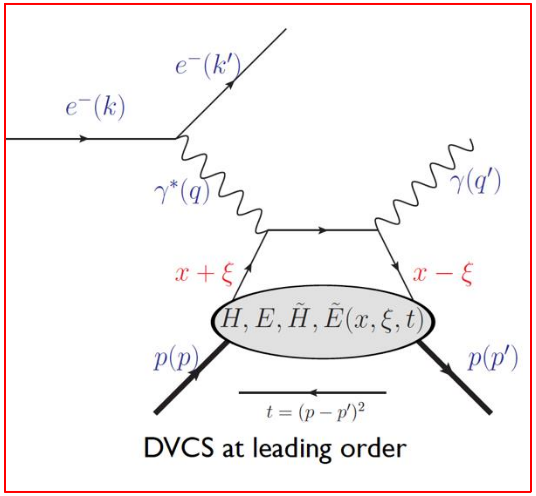
$$H_T^q, \tilde{H}_T^q, E_T^q, \bar{E}_T^q = 2\tilde{H}_T^q + E_T^q$$

DVCS

- Deeply Virtual Compton Scattering is the cleanest way to study GPDs
- GPDs appear in the DVCS amplitude as Compton Form Factor (CFF)

$$\mathcal{H} = \int_{-1}^{1} H(x,\xi,t)\Big(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\Big)dx$$

- DVCS accesses only chiral-even GPDs due to suppression of the helicity flip amplitude



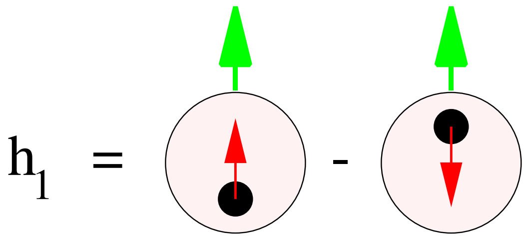
$$\xi = \frac{x_B}{2 - x_B}$$

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

x *is not experimentally accessible*

Chiral-odd GPDs

- The chiral-odd GPDs are difficult to access since subprocesses with quark helicity-flip are usually strongly suppressed
- Very little known about the chiral-odd GPDs
- 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

Link of Transversity GPDs to tensor magnetic moment and tensor charge

- Proton anomalous tensor magnetic moment

$$\kappa_T^u = \int dx \bar{E}_T^u(x, \xi, t = 0)$$

$$\kappa_T^d = \int dx \bar{E}_T^d(x, \xi, t = 0)$$

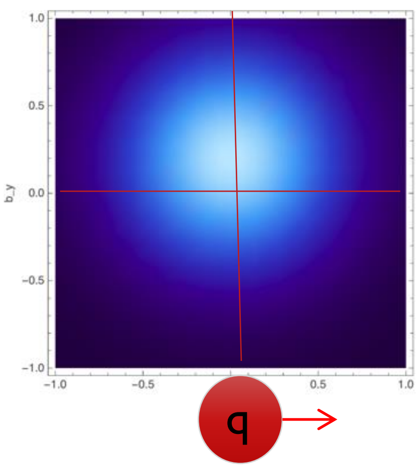
- Proton tensor charge

$$\delta_T^u = \int dx H_T^u(x, \xi, t = 0)$$

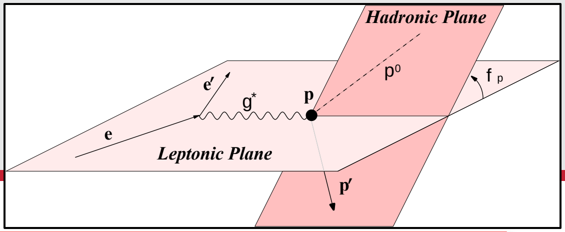
$$\delta_T^d = \int dx H_T^d(x, \xi, t = 0)$$

- Density of transversity polarized quarks in an unpolarized proton in the transverse plane

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



DVMP Leading Twist

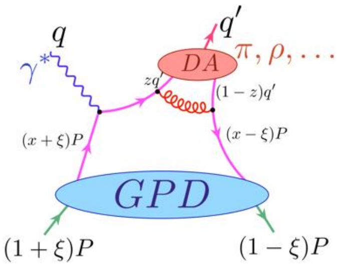


$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}(\sigma_T + \epsilon\sigma_L + \epsilon\cos 2\phi_\pi \sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \sigma_{LT})$$

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

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

At large Q^2 and W, but for fixed x_B and $|t|<<Q^2$ the amplitudes for exclusive meson electroproduction factorize into GPDs and hard scattering subprocess.
The contributions from σ_L dominates in that regime while σ_T is suppressed by $1/Q^2$.
However it is theoretically unknown how large Q^2 and W must be for factorization concept to hold.

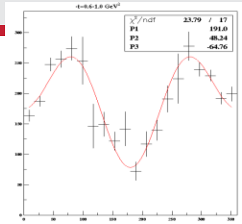


J.C. Collins, L. Frankfurt, and M. Strikman

Factorization theorem for hard exclusive electroproduction of mesons in QCD, Phys. Rev. D **56**, 2982 (1997)

$$\sigma_L \sim \frac{1}{Q^6}$$
$$\frac{\sigma_T}{\sigma_L} \sim \frac{1}{Q^2}$$
$$Q^2 \to \infty \quad x_B, t \ fixed$$

Leading Twist Failed to describe experimental data



- Cross section was off by an order of magnitude
- No ϕ modulation

From extensive experimental and theoretical investigations it turned out that for deeply virtual electroproduction of pseudoscalar mesons $\sigma_L \ll \sigma_T$.

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

σ_L suppressed by a factor coming from:

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

σ_T enhanced by chiral condensate μ_π/Q

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

G. Goldstein, J. Hermandez and S. Liuti

PHYSICAL REVIEW D 84, 034007 (2011)

Flexible parametrization of generalized parton distributions from deeply virtual Compton scattering observables

Gary R. Goldstein,[1,*] J. Osvaldo Gonzalez Hernandez,[2,†] and Simonetta Liuti[2,‡]

[1]Department of Physics and Astronomy, Tufts University, Medford, Massachusetts 02155, USA
[2]Department of Physics, University of Virginia, Charlottesville, Virginia 22901, USA
(Received 16 February 2011; published 5 August 2011)

S. Goloskokov and P. Kroll

Eur. Phys. J. A (2011) 47: 112
DOI 10.1140/epja/i2011-11112-6

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Theoretical Physics

Transversity in hard exclusive electroproduction of pseudoscalar mesons

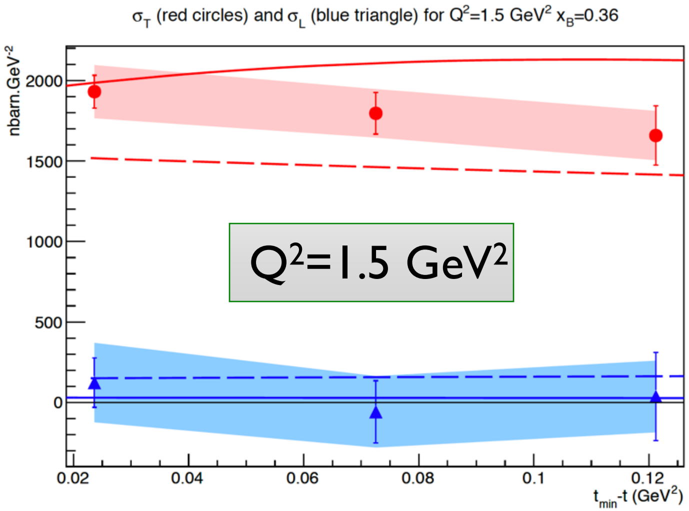
S.V. Goloskokov[1,a] and P. Kroll[2,3,b]

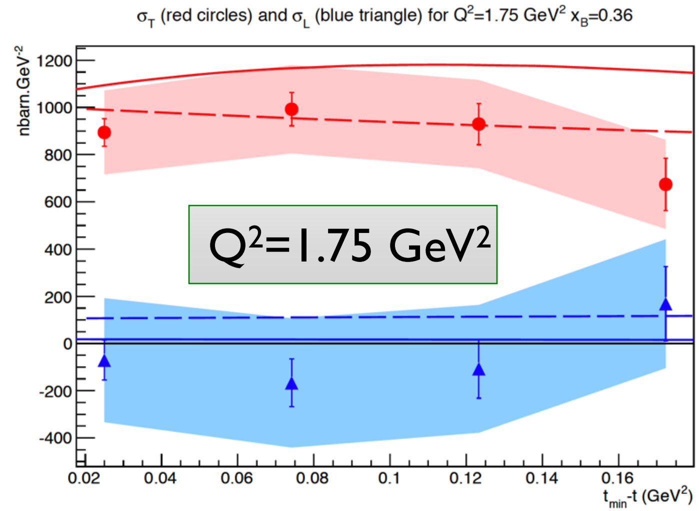
Rosenbluth separation σ_T and σ_L Hall-A at Jefferson Lab

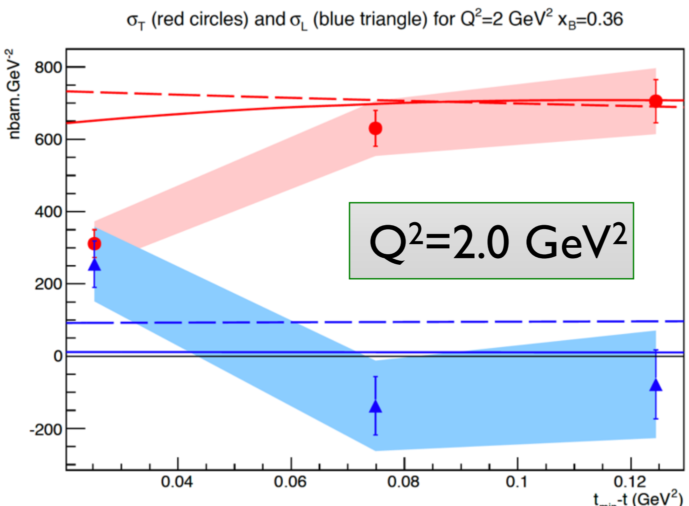
$$ep \rightarrow e'p'\pi^0$$

σ_T

σ_L







- Experimental **proof** that the transverse π^0 cross section is dominant!

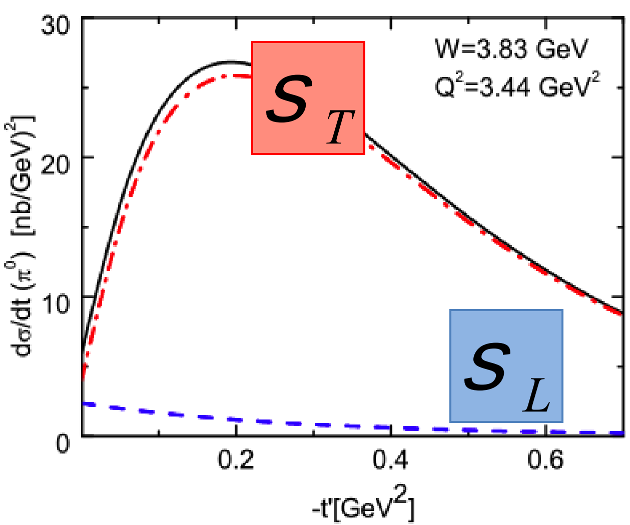
- Hall-A, PRL, 118, 222002 (2017)

Structure functions and GPDs

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

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

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



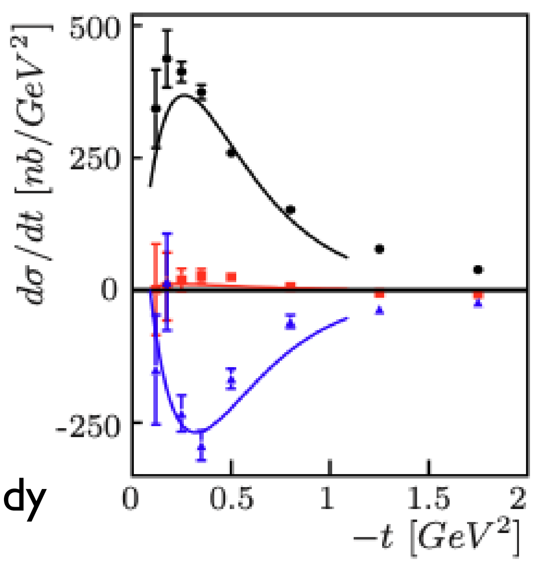
Transversity GPD model

S. Goloskokov and P. Kroll

S. Liuti and G. Goldstein

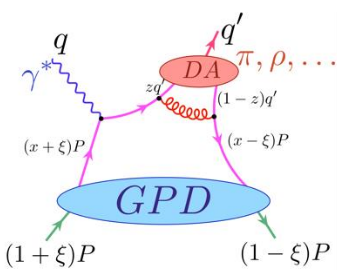
- $\sigma_L << \sigma_T$

It opens the direct way to study the transversity GPDs in pseudoscalar exclusive electroproduction

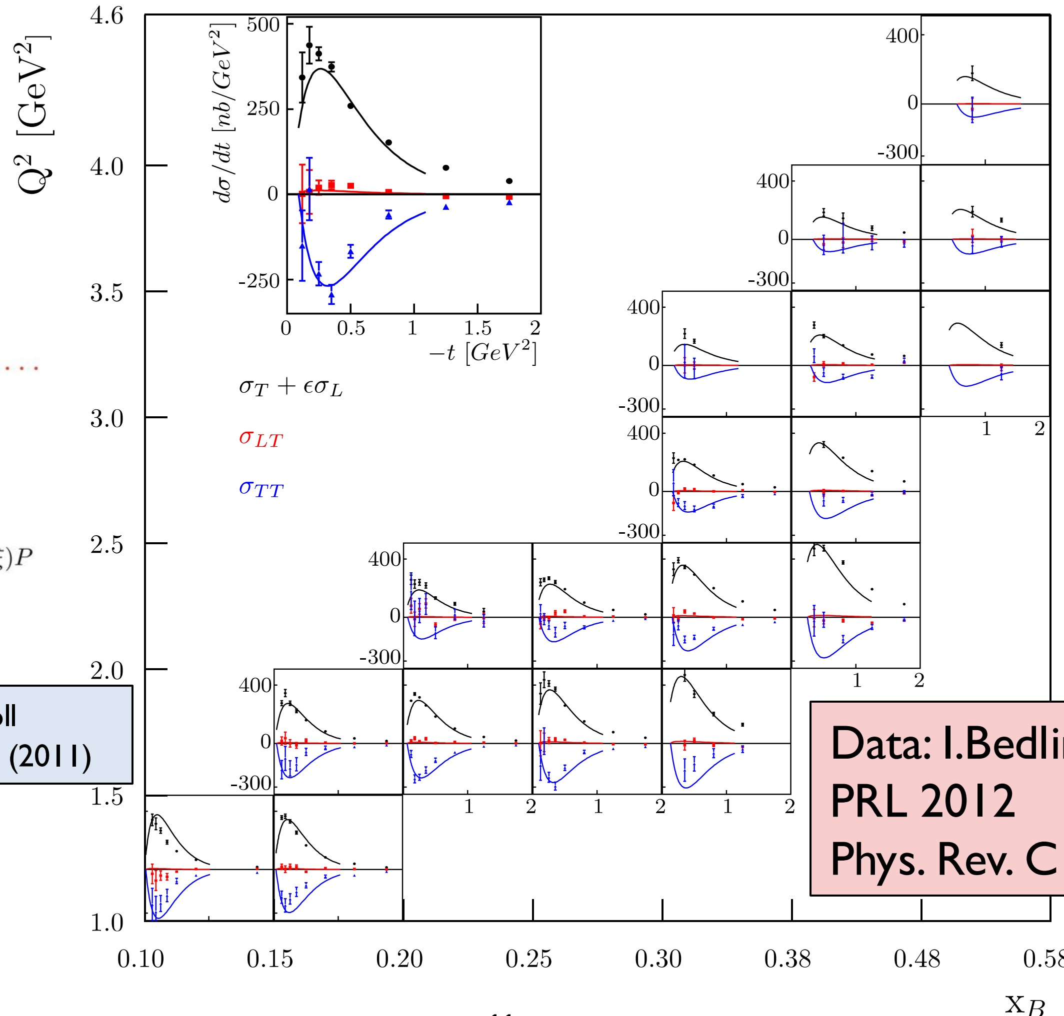


CLAS: π^0 Structure Functions $(\sigma_T + \varepsilon\sigma_L)$ σ_{TT} σ_{LT}

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



Curves: Goloskokov, Kroll
Transversity GPD model (2011)

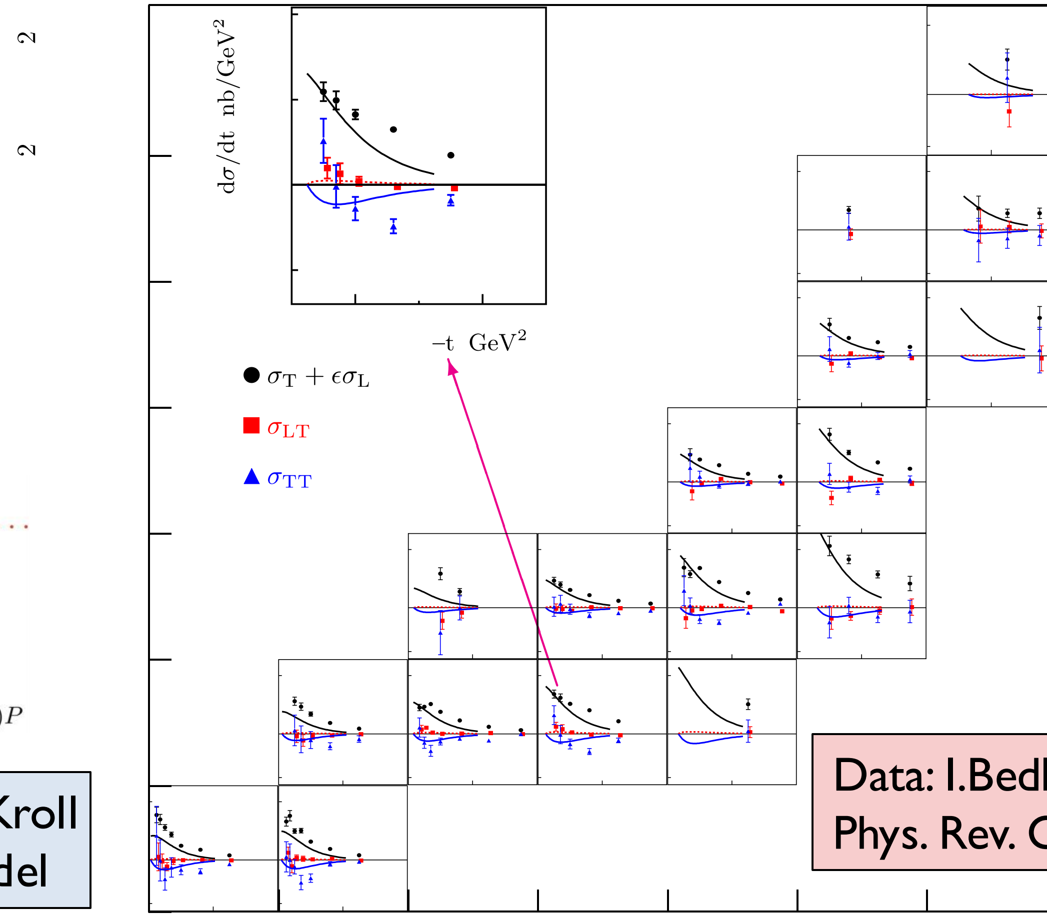


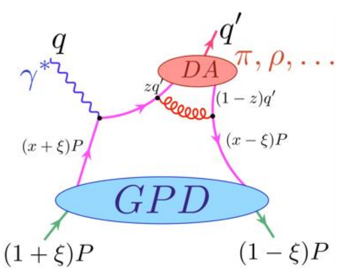
Data: I.Bedlinskiy et al. (CLAS)
PRL 2012
Phys. Rev. C 90, 039901 (2014)

CLAS: η Structure Functions

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

$ep \rightarrow e'p'\pi^0$





Curves: Goloskokov, Kroll
Transversity GPD model

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

B

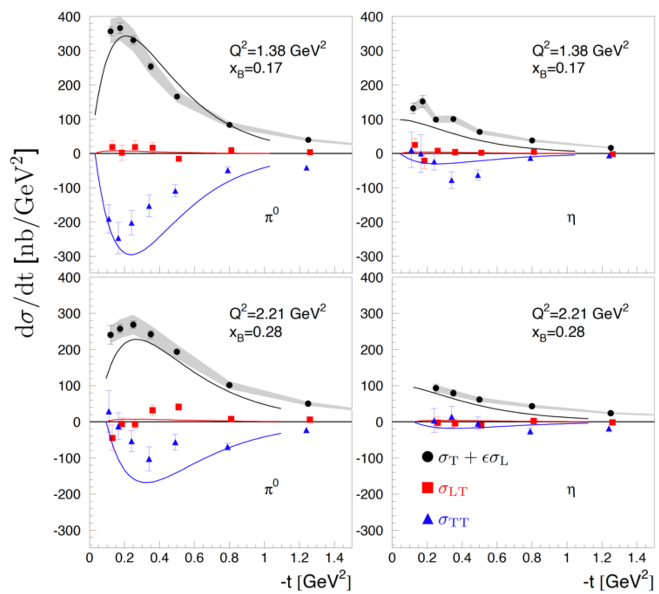
CLAS6 π^0/η Comparison

π^0 | η

σ_u

σ_{LT}

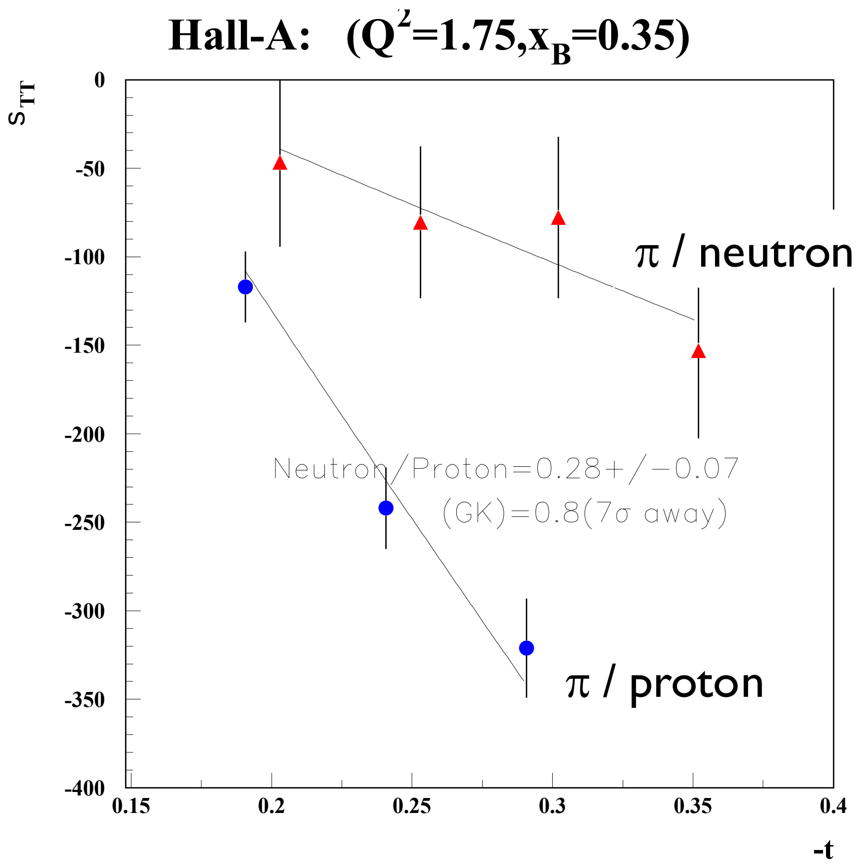
σ_{TT}



CLAS-Phys.Rev.C95(2017)

- 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

Hall-A: σ_{TT} π^0 out of proton and neutron



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

$$\bar{E}_T^{\pi/proton} = \frac{1}{3\sqrt{2}}(2\bar{E}_T^u + \bar{E}_T^d) \quad (1)$$

$$\bar{E}_T^{\pi/neutron} = \frac{1}{3\sqrt{2}}(\bar{E}_T^u + 2\bar{E}_T^d) \quad (2)$$

$$\bar{E}_T^{\eta/proton} = \frac{1}{3\sqrt{6}}(2\bar{E}_T^u - \bar{E}_T^d) \quad (3)$$

Hall-A, PRL, **117**,262001(2016)
Hall-A, PRL, 118, 222002 (2017)

COMPASS

$\mu p \rightarrow \mu p \pi^0$

- 160 GeV/c polarized μ^+ and μ^- beams of the CERN SPS
- Data taken in 2012, within 4 weeks
- **<Q2>=2.0 GeV^2**
- **<xB>=0.093**
- <-t>=0.256 GeV^2

- 0.08 GeV^2 < |t| < 0.64 GeV^2
- 1 GeV^2 < Q2 < 5 GeV^2
- 8.5 GeV < ν < 28 GeV

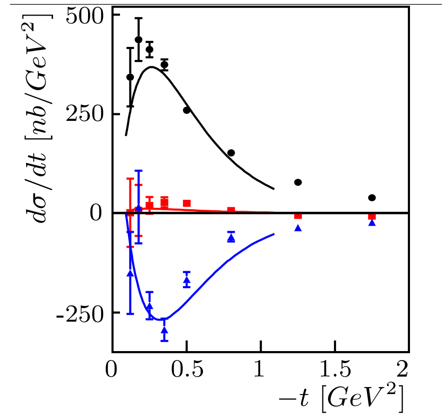
Physics Letters B, Volume 805, 10 June 2020, 135454

COMPASS-Jlab comparison

COMPASS data
(5 points)

- **<Q2>=2.0 GeV²**
- **<xB>=0.093**
- <-t>=0.256 GeV²
- **<ν>=12.8 GeV**

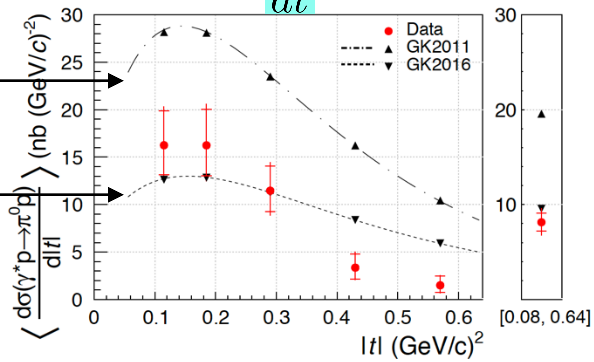
CLAS 2000 points



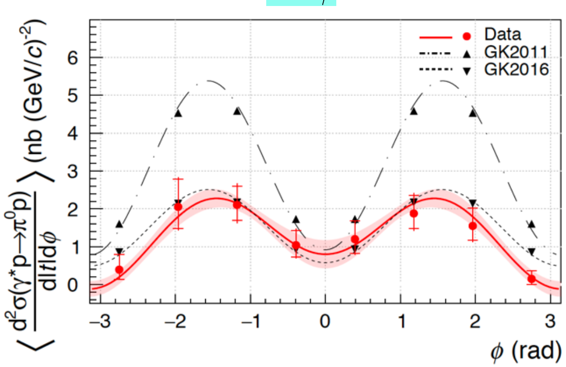
$\frac{d\sigma}{dt}$

GK2011

GK 2016



$\frac{d^2\sigma}{dtd\phi}$



- Factor of two difference between GK2011 and GK2016

Flavor Decomposition

- π^0 (out of proton/neutron)
- η (out of proton)

$$\bar{E}_T^{\pi/proton} = \frac{1}{3\sqrt{2}}(2\bar{E}_T^u + \bar{E}_T^d)$$

$$\bar{E}_T^{\pi/neutron} = \frac{1}{3\sqrt{2}}(\bar{E}_T^u + 2\bar{E}_T^d)$$

$$\bar{E}_T^{\eta/proton} = \frac{1}{3\sqrt{6}}(2\bar{E}_T^u - \bar{E}_T^d - 2\bar{E}_T^s)$$

$$|\eta\rangle = \cos\theta_8 \left|\eta^8\right\rangle - \sin\theta_1 \left|\eta^1\right\rangle$$

GPDs appear in the different flavor combinations

It is shown only octet contribution for η meson for simplicity
The exact formula is very close to the octet one.

For strange quarks $\bar{E}_T^s = \bar{E}_T^{\bar{s}}$, $e_s = -e_{\bar{s}}$

The contribution from sea quarks is cancelled out.

Global fit (in progress)

Data

- CLAS π^0/η out of proton
- Hall-A π^0 out of proton and neutron
- COMPASS π^0
- Fit $\sigma_T+\varepsilon\sigma_L$ *and* σ_{TT} data

$$e+p\to e+\pi^0+p$$
$$e+p\to e+\eta+p$$
$$e+n\to e+\pi^0+n$$
$$\mu+p\to \mu+\pi^0+p$$

GPD Transversity GK Model

Soffer bound: $H_T(x) < \frac{1}{2}[q(x)+\Delta q(x)]$

$$H_T(x,t,\xi=0) = N x^{-\alpha_0}\sqrt{x}(1-x)^3\,[q(x)+\Delta q(x)]\,e^{[b-\alpha'\ln(x)]t}$$

$$\bar{E}_T(x,t,\xi=0) = N\cdot x^{-\alpha_0}(1-x)^n e^{[b-\alpha'\ln(x)]t}$$

$16\ parameters:$

388 experimental points σ_U and σ_{TT} (Q^2, x_B, t)

$$H_T^u(N^u, b^u, \alpha_0^u, \alpha'^u)\quad H_T^d(N^d, b^d, \alpha_0^d, \alpha'^d)$$

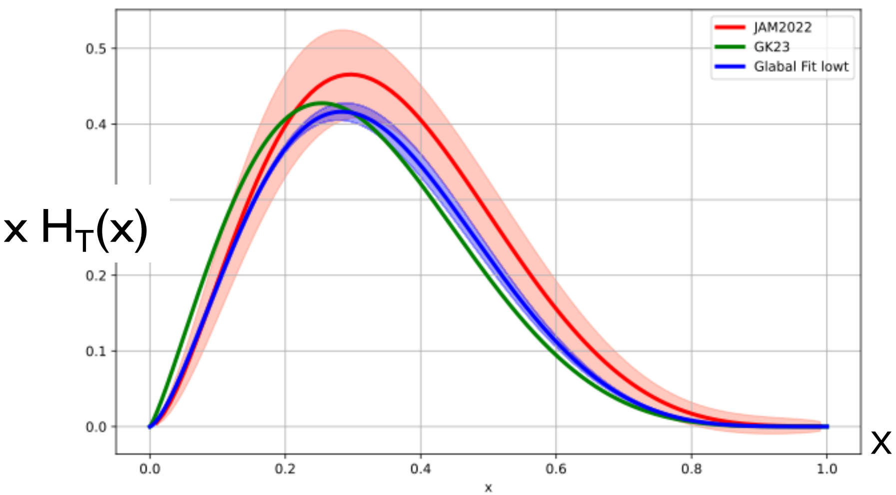
$$\bar{E}_T^u(N^u, b^u, \alpha_0^u, \alpha'^u)\quad \bar{E}_T^d(N^d, b^d, \alpha_0^d, \alpha'^d)$$

A. Kim (Uconn), V.K.

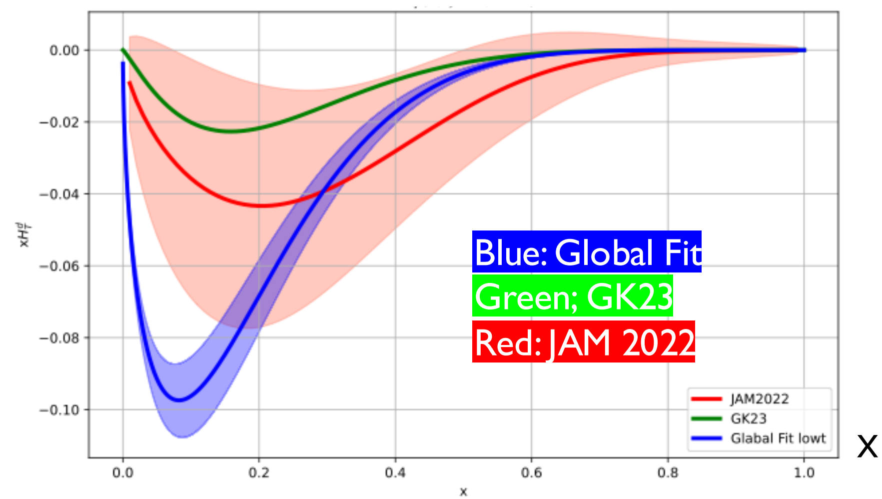
Global Fit: H_T Forward limit

$$H_T^q(x,0,0) = h_1^q(x)$$

u-quark



d-quark



JAM – Jefferson Lab Angular Momentum Collaboration
Global Fit SIDIS, e+e- and p-p with transversity polarized beams.
Transversity GPDs, extracted from different reactions, show remarkable consistency with each other.

Proton Tensor charge

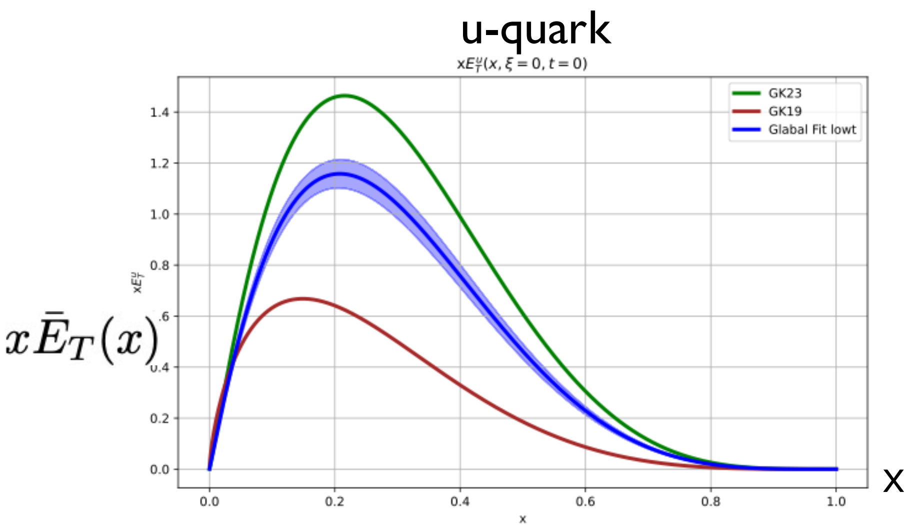
$$\delta_T^u = \int dx H_T^u(x,\xi,t=0)$$

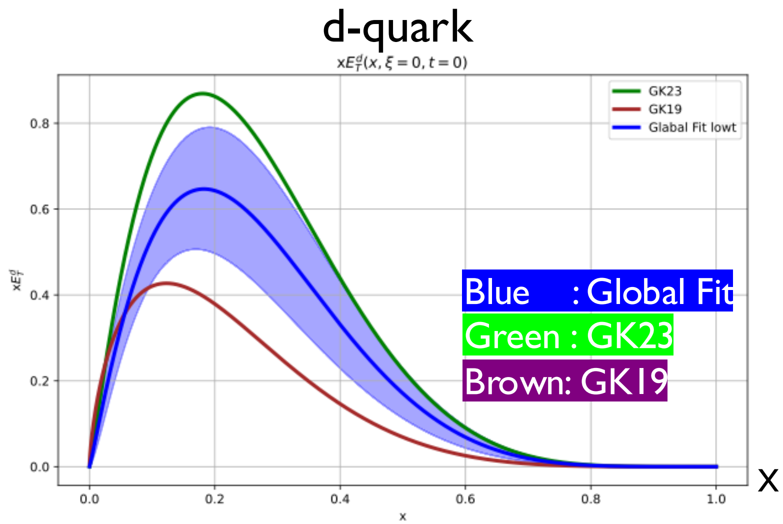
$$\delta_T^d = \int dx H_T^d(x,\xi,t=0)$$

	Lattice QCD	Global Fit	JAM24
δ^u	0.763(32)	0.72(1)	0.78(11)
δ^d	-0.200(21)	-0.35(3)	-0.12(11)
Isovector tensor charge δ^u -δ^d	0.961(32)	1.07(4)	0.90(5)

Lattice QCD: Arxiv:2408.14370
JAM:Phys.Rev.D 109 (2024) 3, 034024,*Phys.Rev.Lett.* 132 (2024) 9, 091901
Phys.Rev.D 106 (2022) 3, 034014

Global Fit: $\bar{E}_T(x)$ Forward limit. Proton Anomalous Tensor Magnetic Moment





The close results between the models and the global fit confirm the fact that extracting such important parameters as the proton tensor charge and the anomalous tensor magnetic moment is meaningful and sufficiently accurate.

$$\kappa_T^u = \int dx \bar{E}_T^u(x,\xi,t=0)$$

$$\kappa_T^d = \int dx \bar{E}^d(x,\xi,t=0)$$

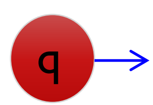
Proton Anomalous Tensor Magnetic Moment

	Lattice QCD	Global Fit	Chiral Soliton model
κ_T^u	2.07	2.74(12)	3.56
κ_T^d	1.35	1.49(28)	1.83

The Density of Transversely Polarized Quarks in an Unpolarized Proton

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

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



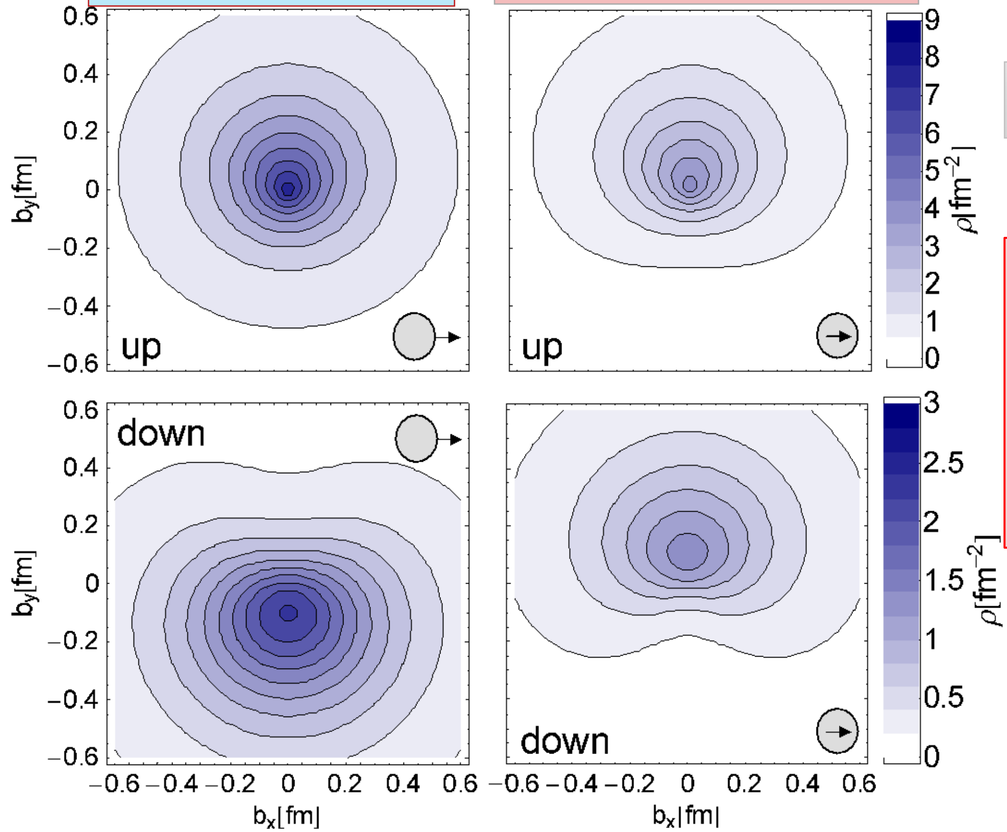
Integrated over *x* Transverse Densities for u and d Quarks in the Proton

Polarized proton

Unpolarized proton

u quarks

Lattice calculations



Strong distortions for unpolarized quarks in transversely polarized proton

Strong distortions for transversely polarized quarks in an unpolarized proton

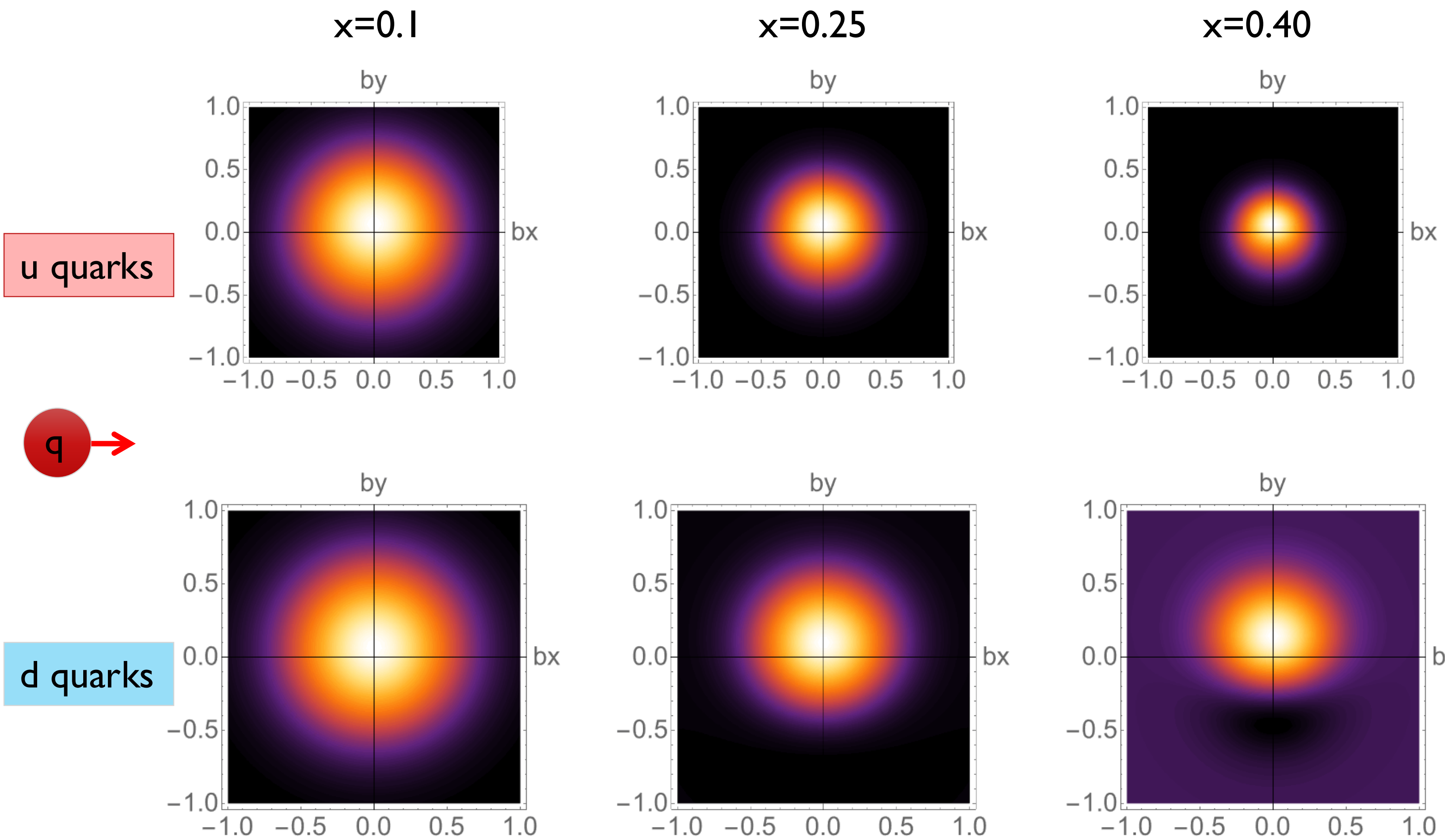
d quarks

Controlled by E

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

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

Density of transversely polarized quarks in an unpolarized proton (Global Fit)



Note distortions for transversely polarized u and d quarks.

First Results from CLAS12

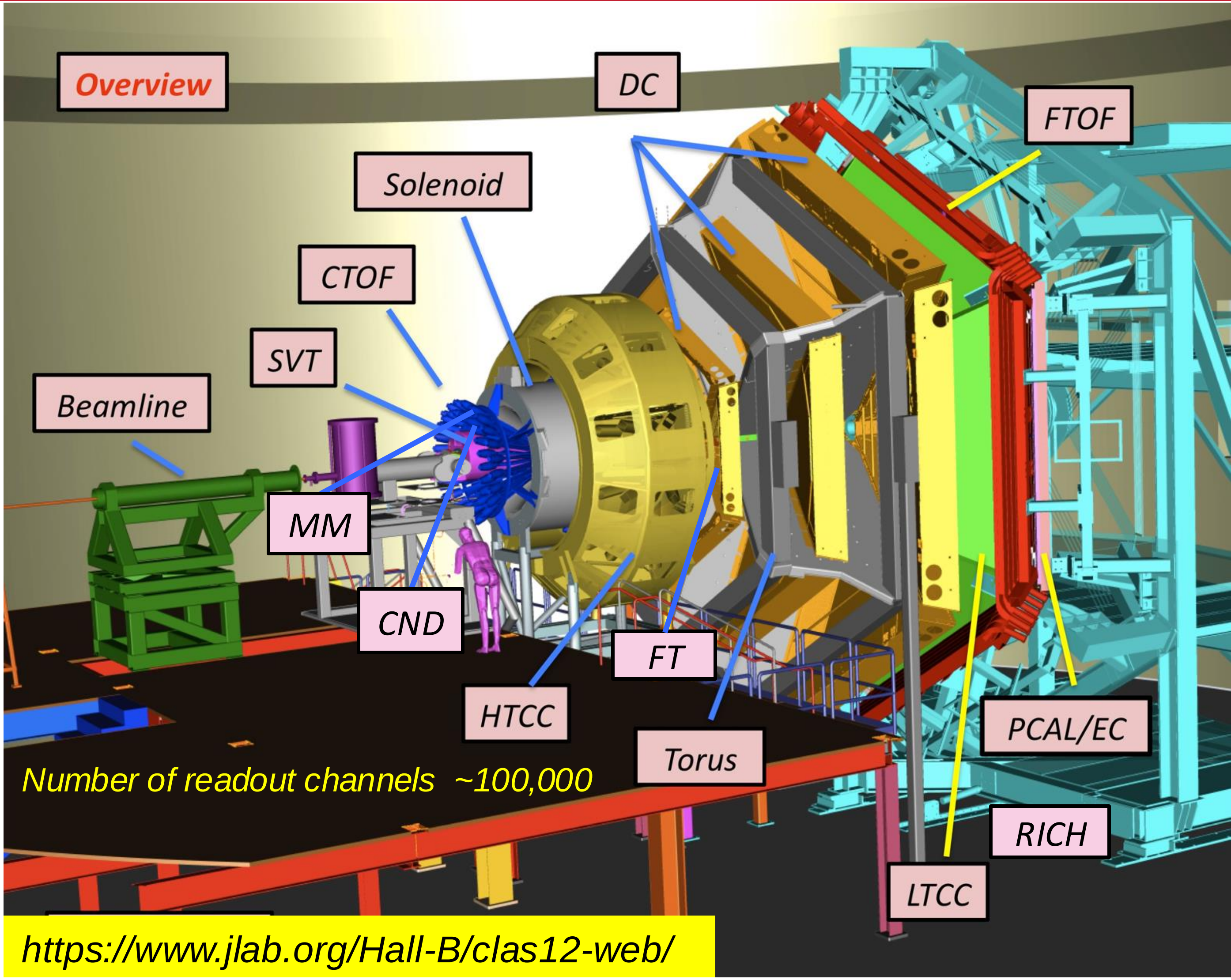
Central Detector:

- *SOLENOID magnet*
- *Barrel Silicon Tracker*
- *Micromegas*
- *Neutron detector*
- *Central Time-of-Flight*

Forward Detector:

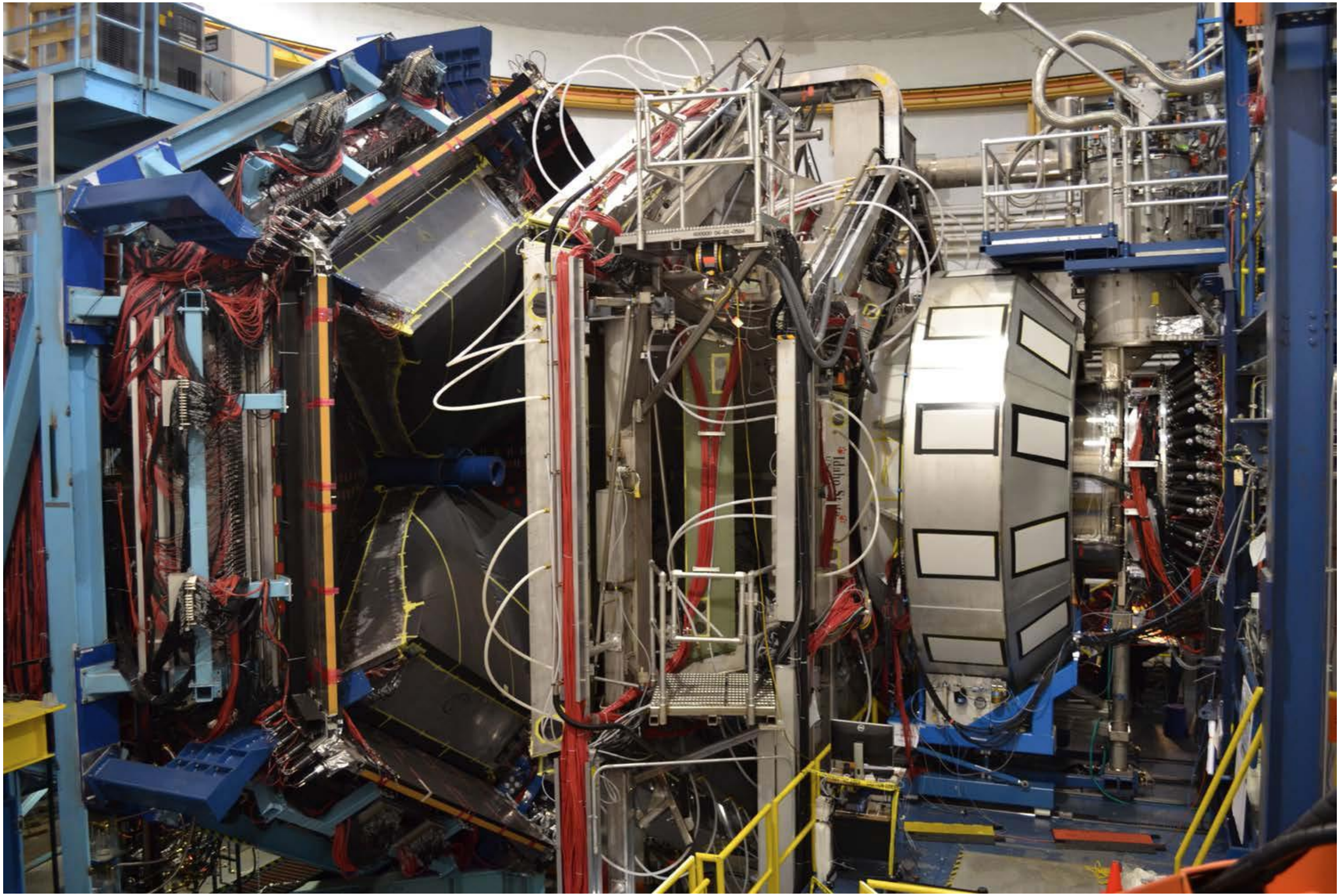
- *TORUS magnet*
- *HT Cherenkov Counter*
- *Drift chamber system*
- *LT Cherenkov Counter*
- *RICH detector*
- *Forward ToF System*
- *Preshower calorimeter*
- *E.M. calorimeter (EC)*

Forward Tagger *(FD)*



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

CLAS12 installed in Hall-B of Jlab



CALS12 Program

- Asymmetries, Cross sections at different beam energies 10.6, 7.5 and 6.5 GeV: RGA, RGB, RGK

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

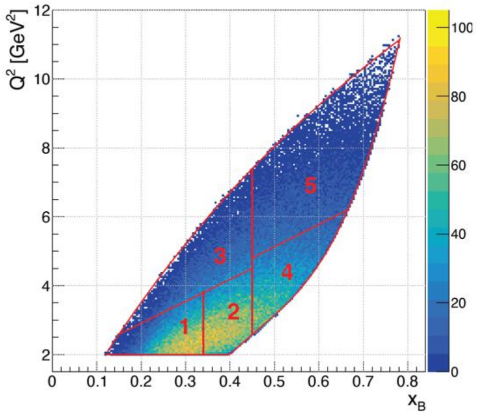
- Asymmetries:

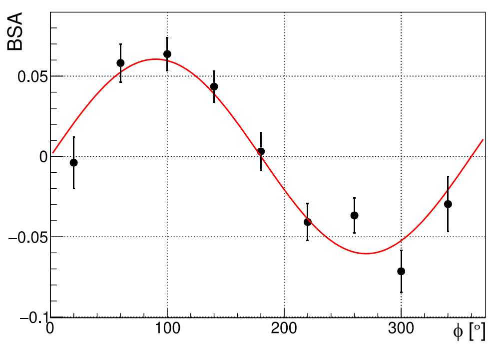
$\mathcal{A}_{LU}$ – *beam spin* — π^0 published

$\mathcal{A}_{UL}$ – *target spin*

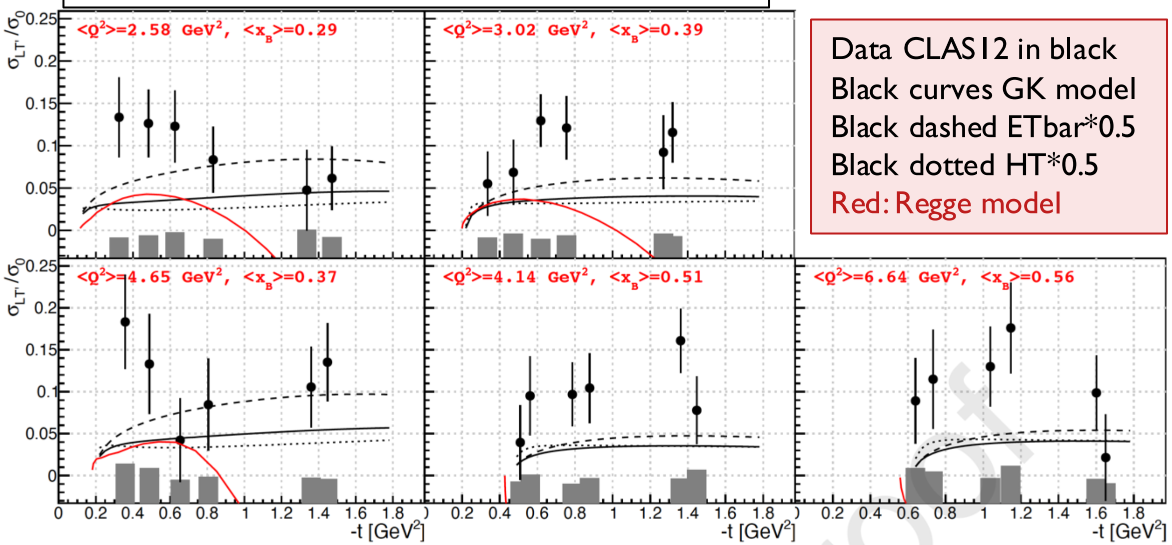
$\mathcal{A}_{LL}$ – *beam target*

CLAS12 Beam Spin Asymmetry $ep \to e'p'\pi^0$





$$\frac{\sigma_{LT'}}{\sigma_0} \sim \frac{Im[\langle \bar{E}_T\rangle^* \langle \widetilde{H}\rangle + \langle H_T\rangle^* \langle \widetilde{E}\rangle]}{(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle \bar{E}_T\rangle\right|^2 + \epsilon\sigma_L}$$

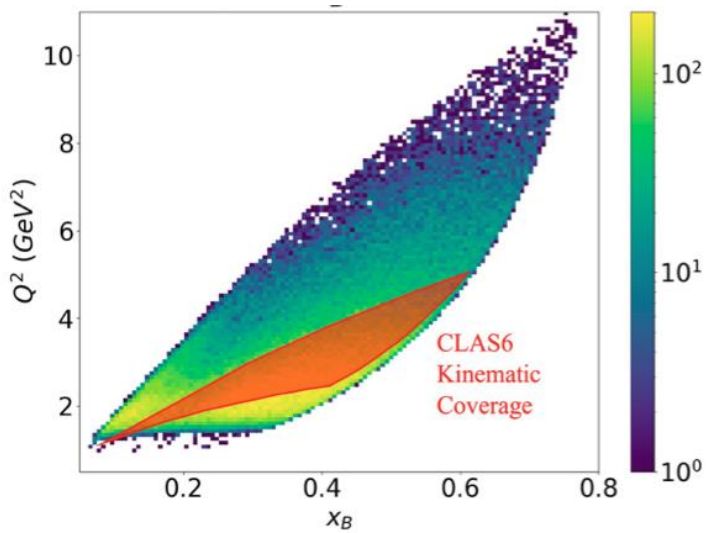


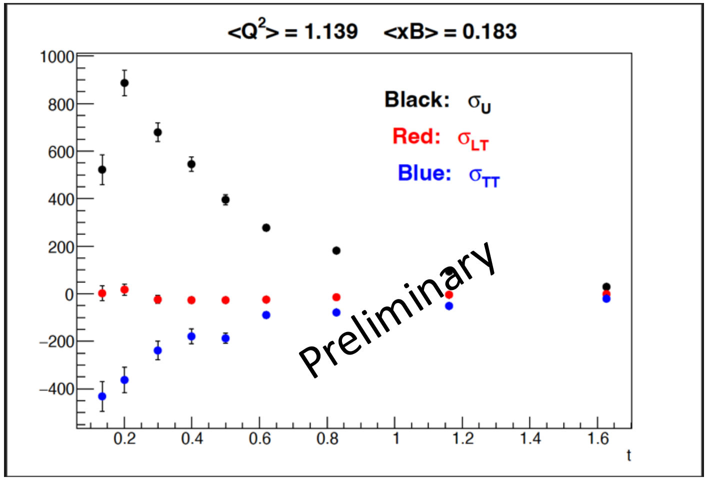
Data CLAS12 in black
Black curves GK model
Black dashed ETbar*0.5
Black dotted HT*0.5
Red: Regge model

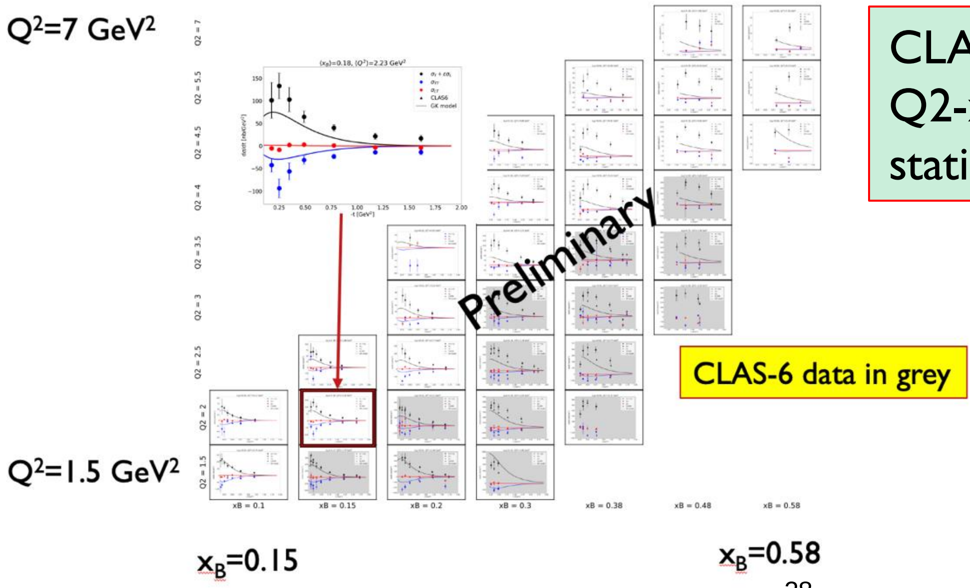
The GK model predicts significantly smaller values of BSA. This has been a serious issue for the model over the years. And currently, there is no clear solution for correcting it.

A. Kim, S. Diehl, K.Joo,VK et. al
Phys.Lett.B 849 (2024) 138459
e-Print: 2307.07874 [nucl-ex]

CLAS12 Preliminary







CLAS12 offers a significant advantage in Q2-xB-t coverage, along with higher statistics. Data analysis is in progress.

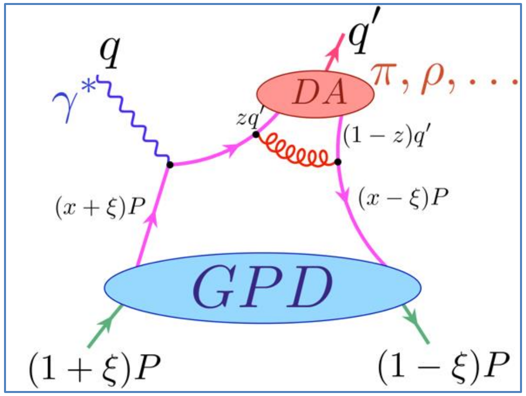
Summary

- The study of deeply virtual exclusive *pseudoscalar* meson production uniquely connected with the transversity GPDs, and has already begun to access their underlying polarization distributions of quarks in the nucleon.
- The combined π^0 and η, proton and neutron data analysis provide the way for the flavor decomposition of transversity GPD
- The global analysis of the full data set from CLAS, Hall-A and COMPASS is underway with main goal to get the transversity GPD parameters with flavor decomposition
- The CLAS12 detector successfully took data with proton and deuteron targets with 10.6, 7.5 and 6.5 GeV electron beam. The analysis of these data will significantly increase the kinematic coverage and robustness of the accessing the Transversity GPDs.

Support Slides

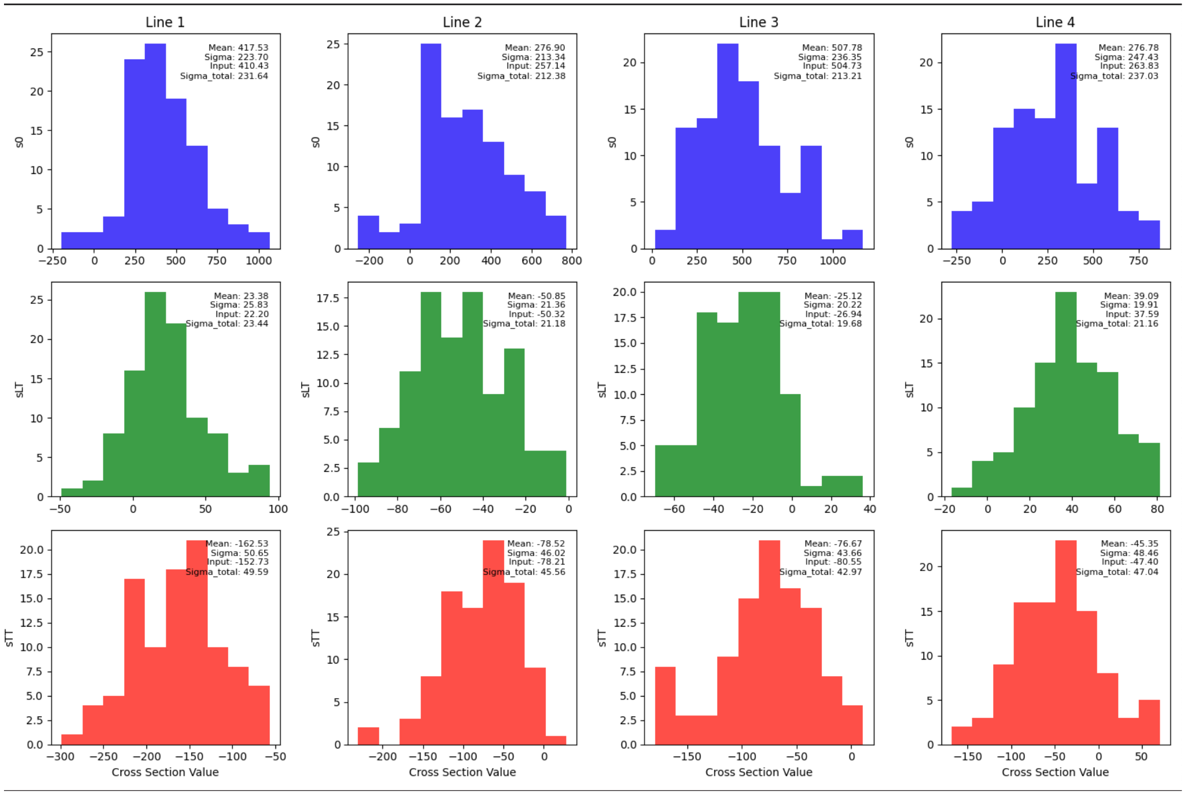
Goloskokov-Kroll Model

- GPDs are constructed from the double distribution ansatz
- Generalized Formfactors represent a convolution of GPDs with subprocess amplitude
- The subprocess amplitude calculated in the impact parameyer space
- Transverse momenta of the quark and the anti-quark are kept in the twist-3 meson distribution amplitude
- The gluon radiations are taken into account through Sudakov factor



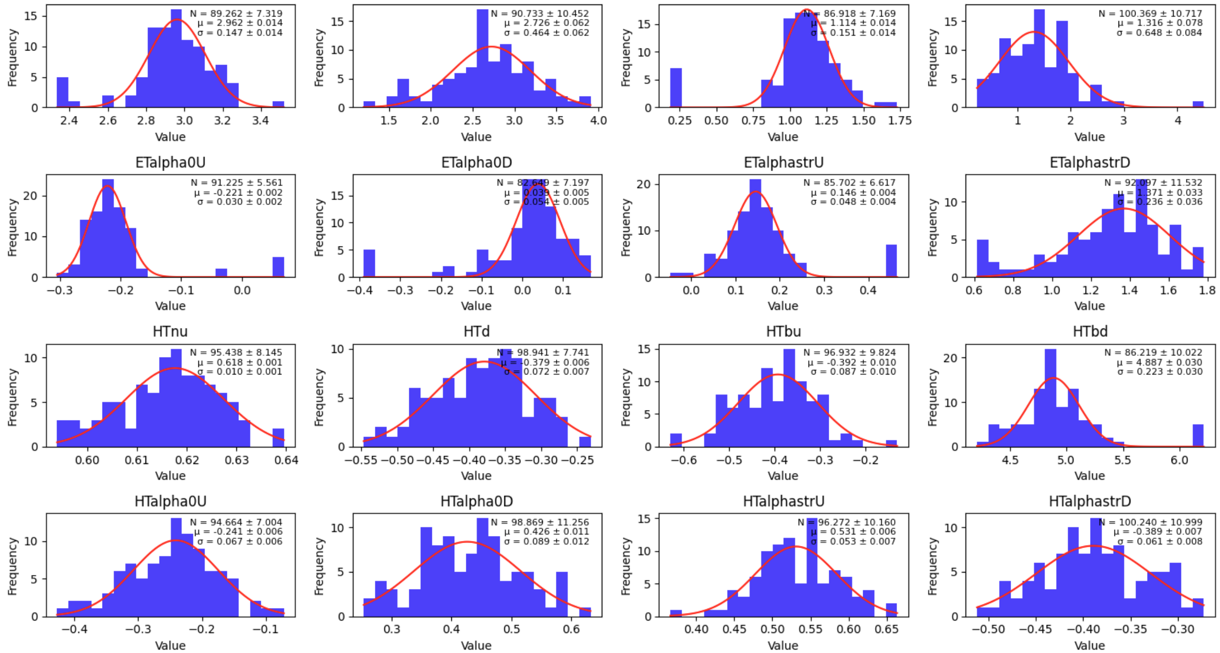
- S.V. Goloskokov and P. Kroll. Transversitry in hard exclusive electroproduction of pseudoscalar mesons. *Eur.Phys.J.A* 47 **(2011)** 112, e-Print: 1106.4897 [hep-ph]
- P. Kroll et all. *Phys.Rev.D* 109 **(2024)** 3, 034008, e-Print: 2312.13164 [hep-ph]

Replica: Generator for Replica Fits



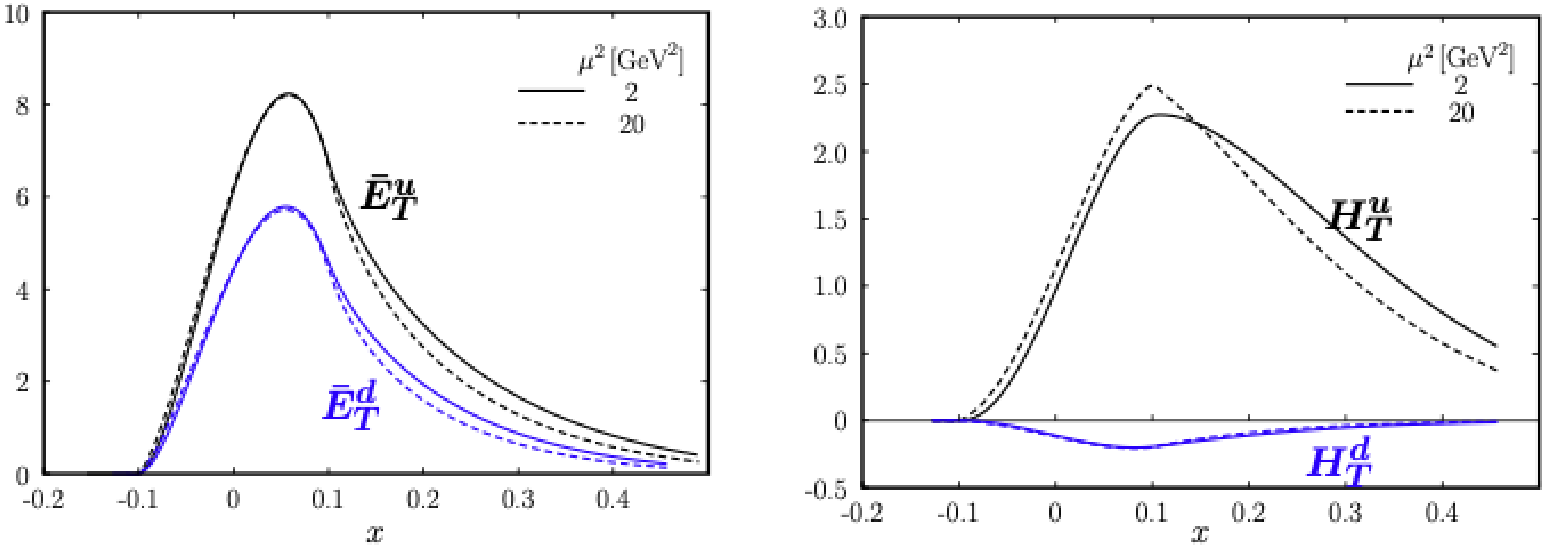
Generate 100 replica files for 194 data points used by Global Fit.
Keep sigma and generate mean in accordance with the original fata file.

Replica Fit Results



Fit 100 replica data file and plot fit results for 16 parameters used by Global Fit.
Mean and sigma from the fit of these distribution are Fit Parameters and Error.
The result for fit and error bars are compatible with the Fit of the original data set.
It confirms that fir is stable.

Evolution of the Transversity GPDs $\bar{E}_T$ *and* H_T



- It turns out that that the evolution of the transversity GPDs is a minor effect within the range of scales accessible to current experiments. The figure presents $\bar{E}_T$ ***and HT*** at the scales μ=2 and 20 GeV^2.

GK Model Uncertainties

ep ® $ep\rho^0$

σ_U

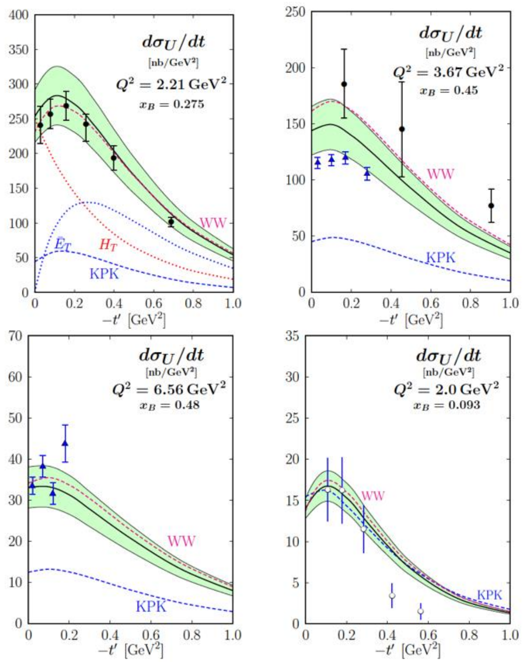


Figure 5: The unseparated cross section versus t' for various kinematical settings. The separate contributions from H_T and $\bar{E}_T$ are shown as dotted lines for $Q^2 = 2.21$ GeV². The data shown by open circles are taken from [40]. For other notations, see Fig. 4.

σ_{TT}

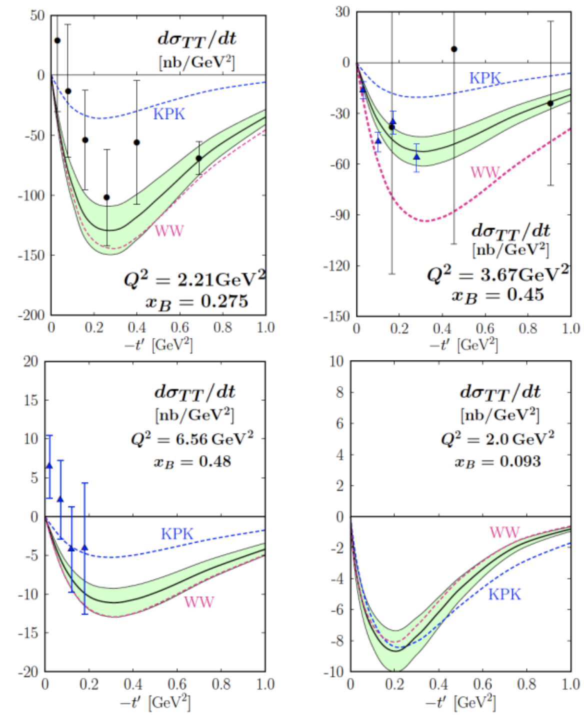


Figure 4: The transverse-transverse interference cross section versus t' for various kinematical settings. The solid lines with error bands (evaluated from the uncertainties of the GPDs and μ_π) are the MPA results evaluated from the DA (20), the dashed lines are evaluated from the DA (19) (KPK) and from the WW approximation (WW). The latter result is taken from [8]. The data are taken from [5] (full circles) and from [39] (triangles). The Hall A data in the upper right plot are at the adjacent kinematics $Q^2 = 3.57$ GeV² and $x_B = 0.36$.

20-25% uncertaincies

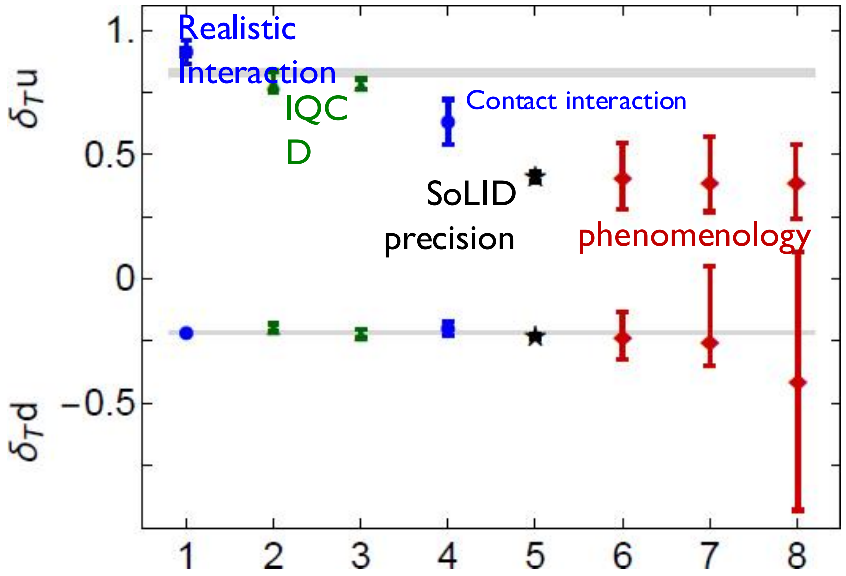
G. Duplančić, P. Kroll, K. Passek-K., and L. Szymanowski
PhysRevD.109.034008, 2024

Proton tensor charges from a Poincaré-covariant Faddeev equation, Qing-Wu Wang, S.-X. Qin, C.D. Roberts and S. M. Schmidt, arXiv:1806.01287 [nucl-th], Phys. Rev. D **98** (2018) 054019/1-10

Proton's Tensor Charges

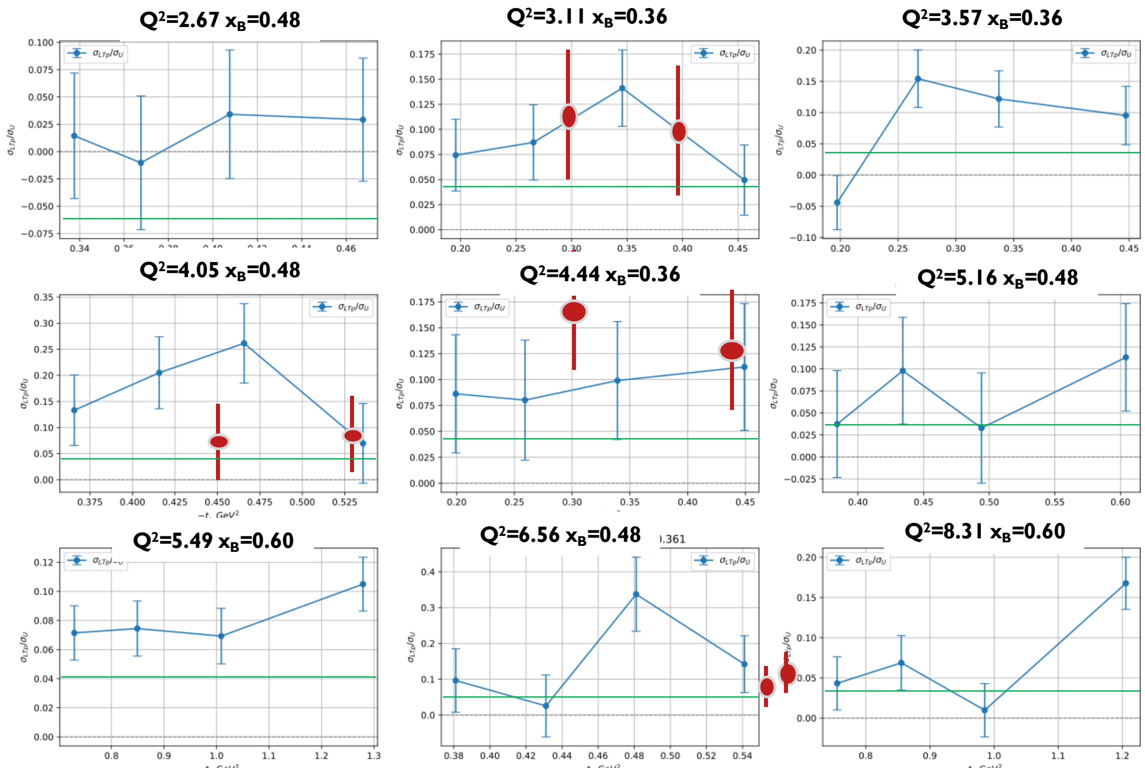
- Faddeev equation predictions
- $\delta_T d$: Theory and Phenomenology agree
  - $\delta_T d \equiv 0$ in models that suppress axial-vector diquark correlations
- $\delta_T u$: Increasing tension between theory and phenomenology
- Theory average

$$\delta_T u = 0.912^{(42)}_{(47)}\,, \qquad \delta_T d = -0.218^{(4)}_{(5)}\,,$$
$$g_T^{(1)} = 1.130^{(42)}_{(47)}\,, \qquad g_T^{(0)} = 0.694^{(42)}_{(47)}$$



$$\overline{\delta_T u} = 0.803(17)\,, \ \overline{\delta_T d} = -0.216(4)$$

2021 Hall-A Beam-Spin Asymmetry



CLAS12
Hall-A
GK model

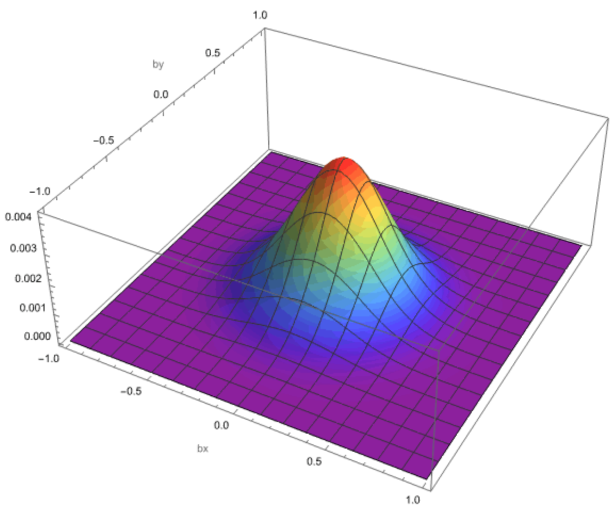
ep ® epp^0

The BSA asymmetry from CLAS12 and Hall A-21 are compatible at similar kinematics. The GK model predicts an asymmetry at the level of 4% (shown in green). Overall, this experiment disagrees with the GK model, similar to the results observed with CLAS.

Phys.Rev.Lett. 127 (2021) 15, 152301

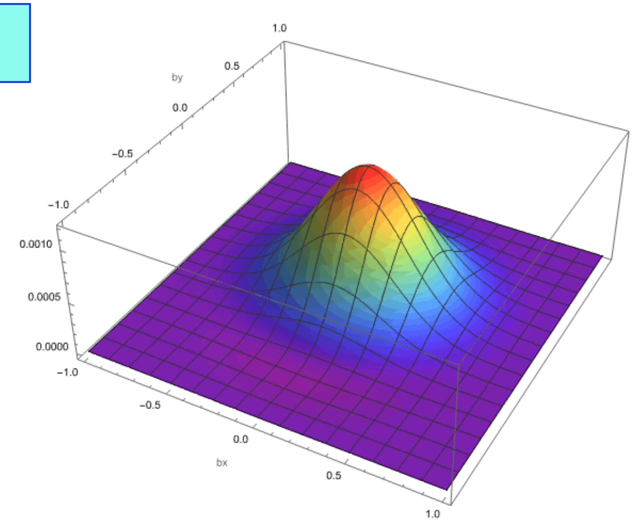
Transverse Densities for Polarized Quarks in Unpolarized Proton

u-quark density



x=0.30

d-quark density



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