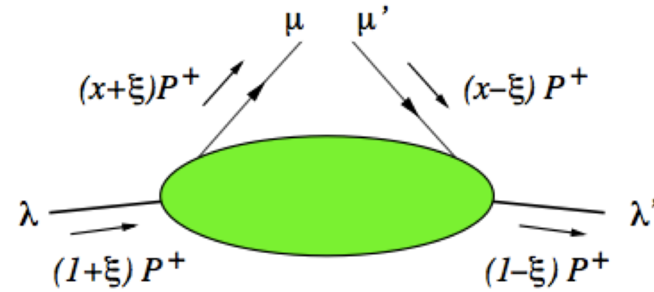
Transverse spin density of the proton and pseudoscaler meson electroproduction

Valery Kubarovsky

Jlab

CLAS Collaboration Meeting, November 15, 2019

Generalized Parton Distributions



- A wealth of information on the nucleon structure is encoded in GPDs.
- 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.
- GPDs are the functions of three kinematic variables: x, ξ and t

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

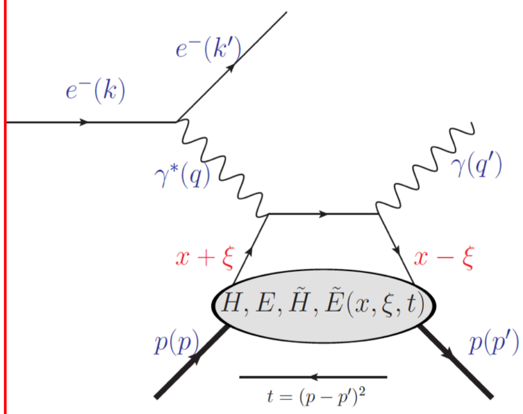
$$H_T^q, \tilde{H}_T^q, E_T^q, \bar{E}_T^q = 2\tilde{H}_T^q + E_T^q$$

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
- Flavor separation is difficult



DVCS at leading order

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

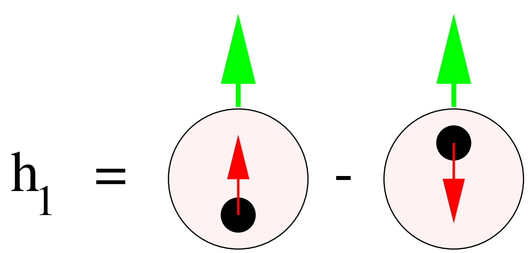
$$t = (p - p')^2$$

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

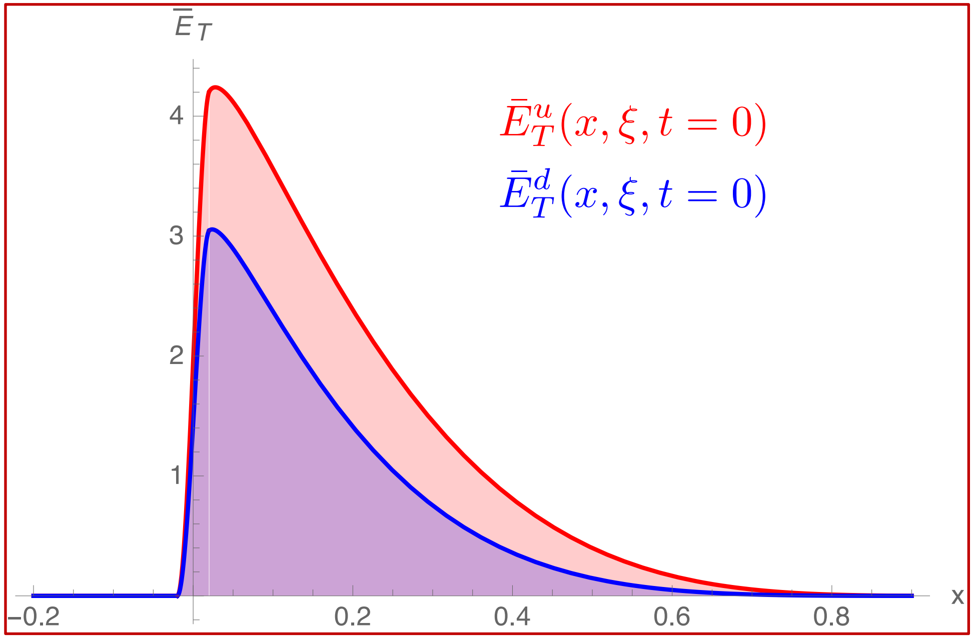


The transversity describes the distribution of transversely polarized quarks in a transversely polarized nucleon

Proton Anomalous Tensor Magnetic Moment

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

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

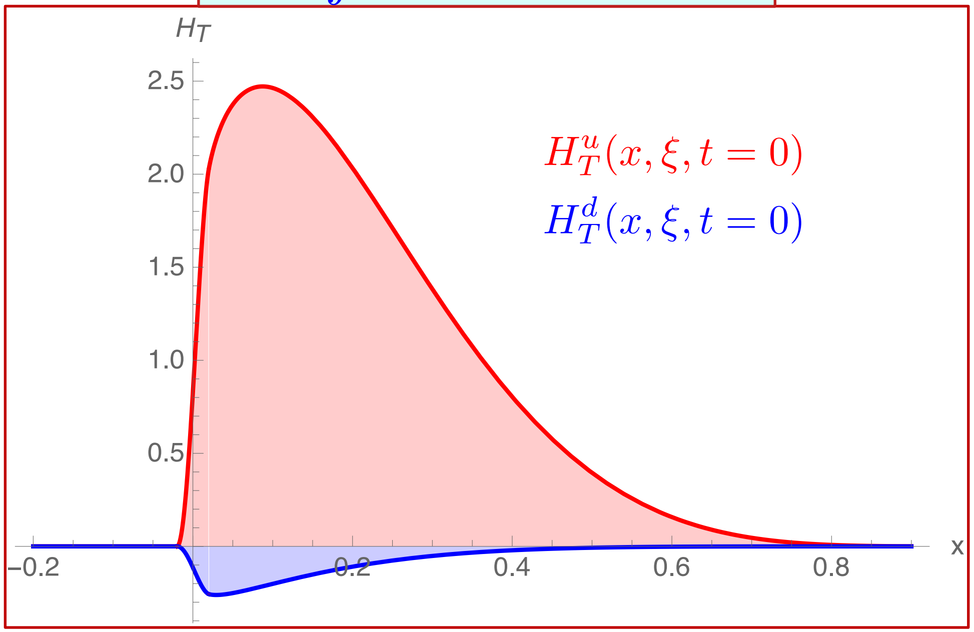


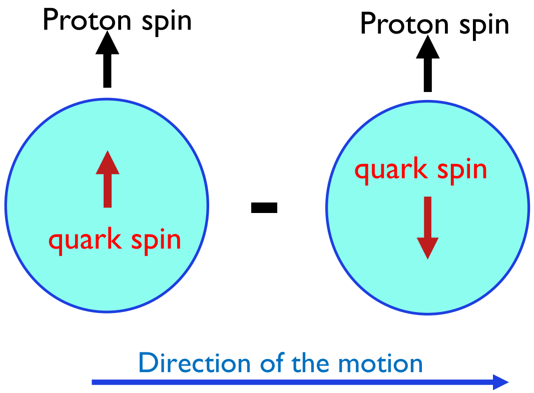
Anomalous tensor magnetic moment induces a sideways shift of the quark density in the transverse to the nucleon motion plane.

Proton Tensor Charge

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

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



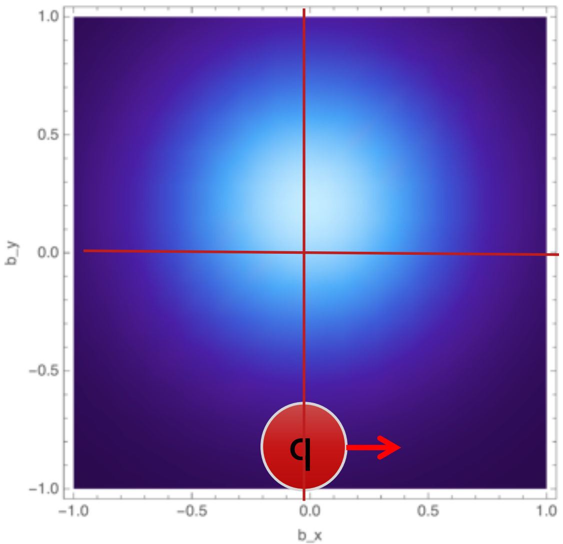


The tensor charge measures
net distribution of transverse
polarized quarks inside a
transversely polarized protor

$\langle P(k,\sigma)|\bar{q}\sigma_{\mu\nu}|P(k,\sigma)\rangle = \delta_T^q \bar{u}(k,\sigma)\sigma_{\mu\nu}u($

he nucleon tensor charge is a fundamental property of the nucleon and its
etermination is among the main goals of existing and future experiments.

Density of Transversely Polarized Quarks in an Unpolarized Proton in the Transverse Plane



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

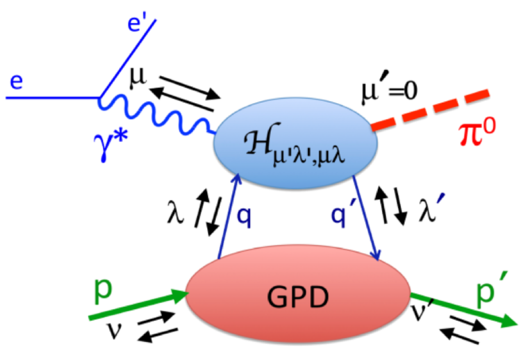
$$\delta(x,\vec{b}) = \frac{1}{2}\left[H(x,\vec{b}) - \frac{b_y}{m}\frac{\partial}{\partial b^2}\bar{E}_T(x,\vec{b})\right]$$

$$ep \to ep\pi^0$$

DVMP Leading Twist

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

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



$$\sigma_L \sim \frac{1}{Q^6}$$

$$\frac{\sigma_T}{\sigma_L} \sim \frac{1}{Q^2}$$

$$Q^2 \to \infty, \quad x_B, t\ fixed$$

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

J.C. Collins, L. Frankfurt, and M. Strikman
Factorization for hard exclusive electroproduction of mesons in QCD
Phys. Rev. D **56**, 2982 (1997)

Leading Twist Failed to describe data

$ep \longrightarrow ep\pi^0$

Leading twist σ_L – dominance, no ϕ modulation

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

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

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

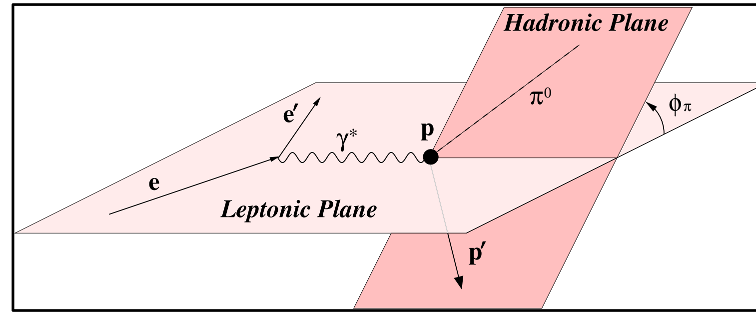
$$\langle\tilde{H}\rangle = \sum_\lambda \int_{-1}^{1} dx M(x,\xi,Q^2,\lambda)\tilde{H}(x,\xi,t)$$

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

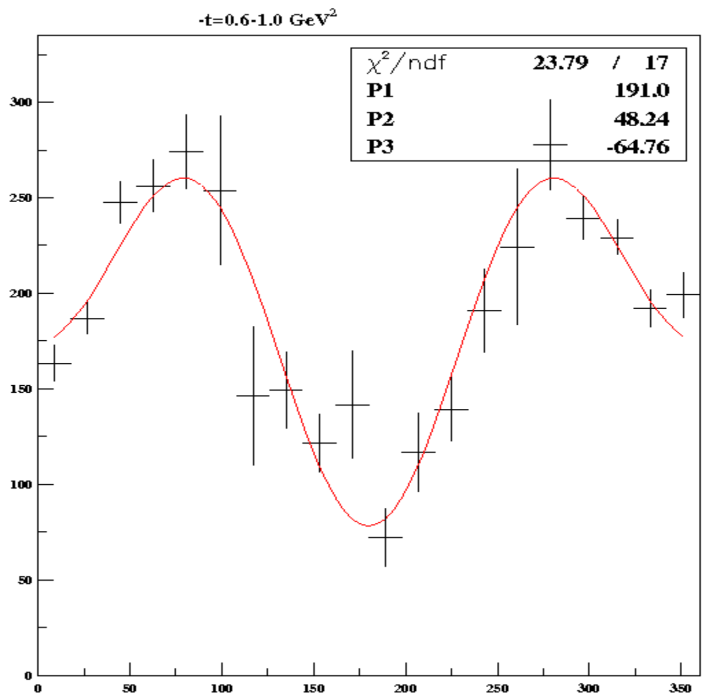
The brackets <F> denote the convolution of the elementary process with the GPD F (generalized form factors)

Structure Functions

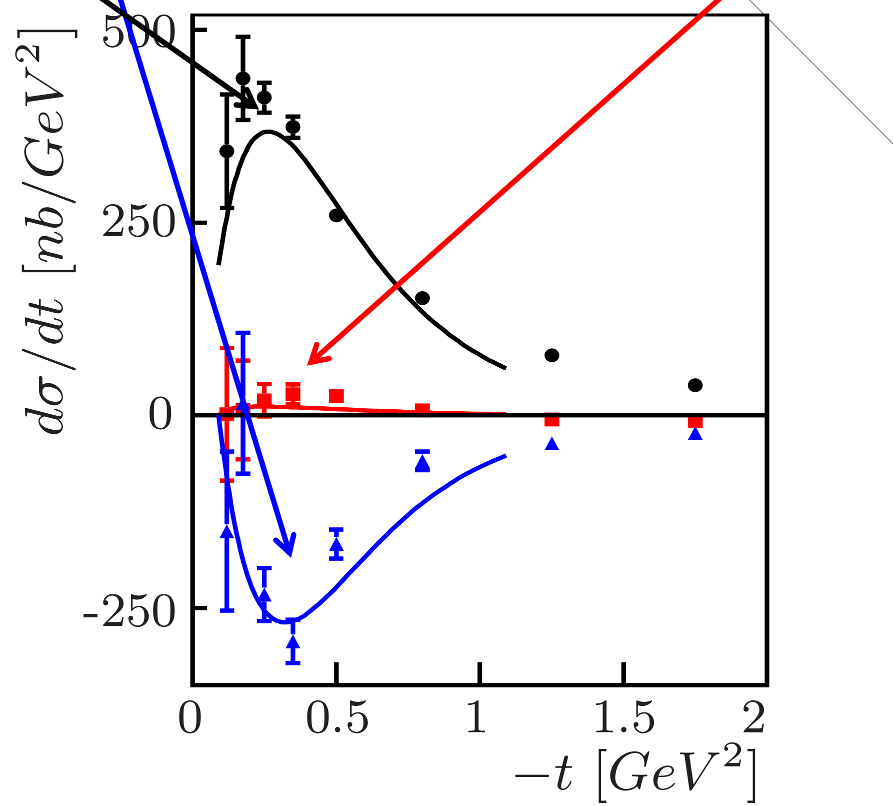
$\sigma_U = \sigma_T + \varepsilon\sigma_L \quad \sigma_{TT} \quad \sigma_{LT}$



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



φ distribution



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

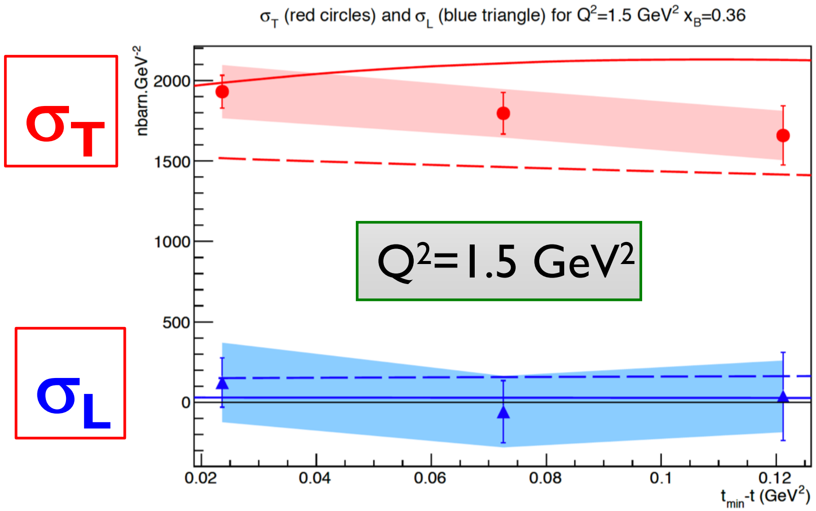
Measurement of Exclusive π^0 Electroproduction Structure Functions and their Relationship to Transverse Generalized Parton Distributions

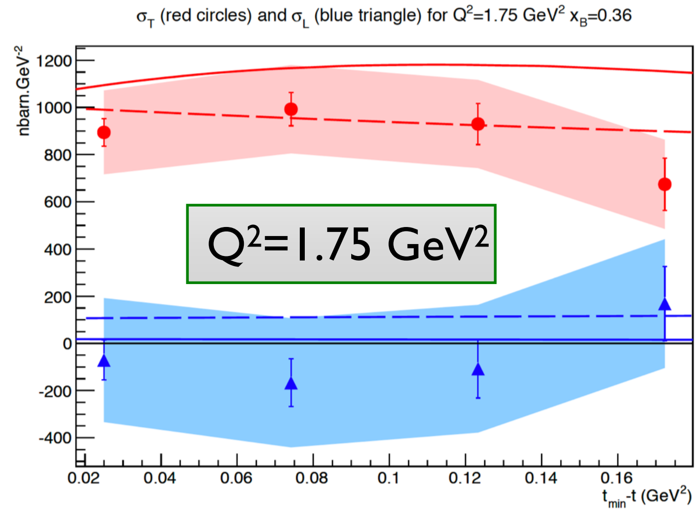
I. Bedlinskiy,[22] V. Kubarovsky,[35,30] S. Niccolai,[21] P. Stoler,[30] K. P. Adhikari,[29] M. Aghasyan,[18] M. J. Amaryan,[29]

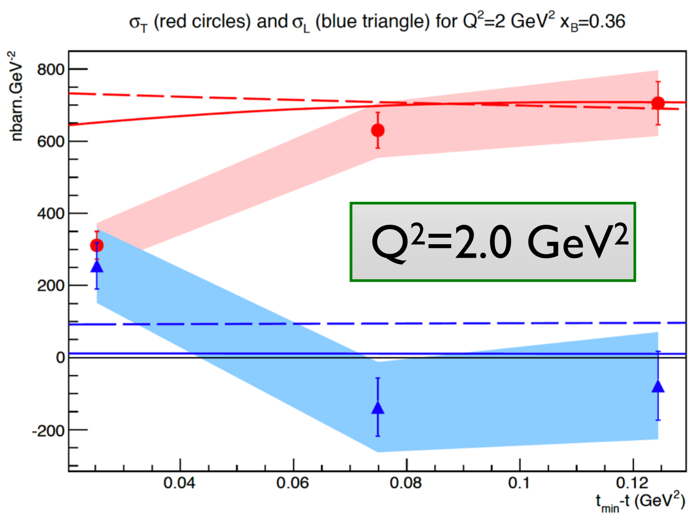
- The measured cross section of π^0 electroproduction is much larger than expected from leading-twist handbag calculation. This means that the contribution of the longitudinal cross section σ_L is small in comparison with σ_T. The same conclusion can be made in a almost model independent way from the 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, PRL, 118, 222002 (2017)

$ep \rightarrow ep\pi^0$

Structure functions and GPDs

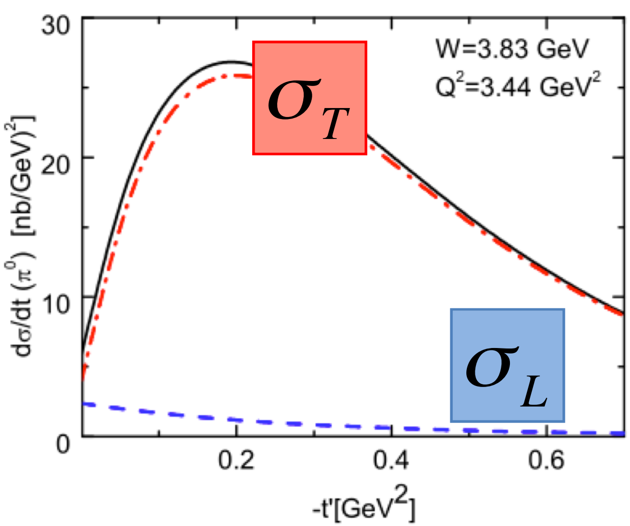
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}(\sigma_T + \epsilon\sigma_L + \epsilon\cos 2\phi_\pi \sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \sigma_{LT})$$

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

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

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

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



Transversity GPD model

S. Goloskokov and P. Kroll

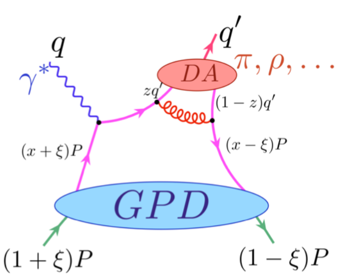
S. Liuti and G. Goldstein

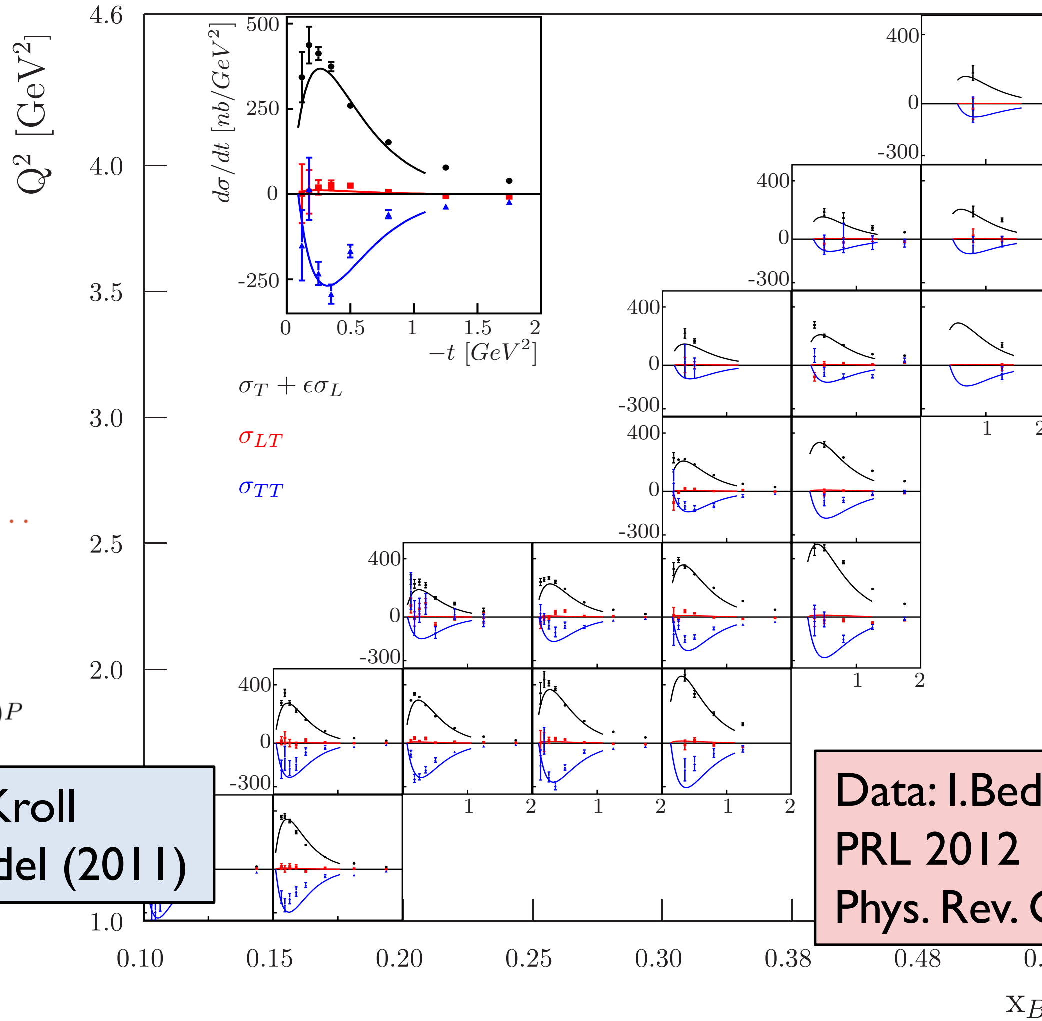
- $\sigma_L << \sigma_T$

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

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

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



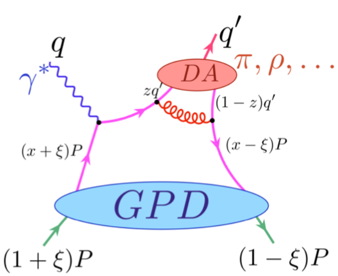


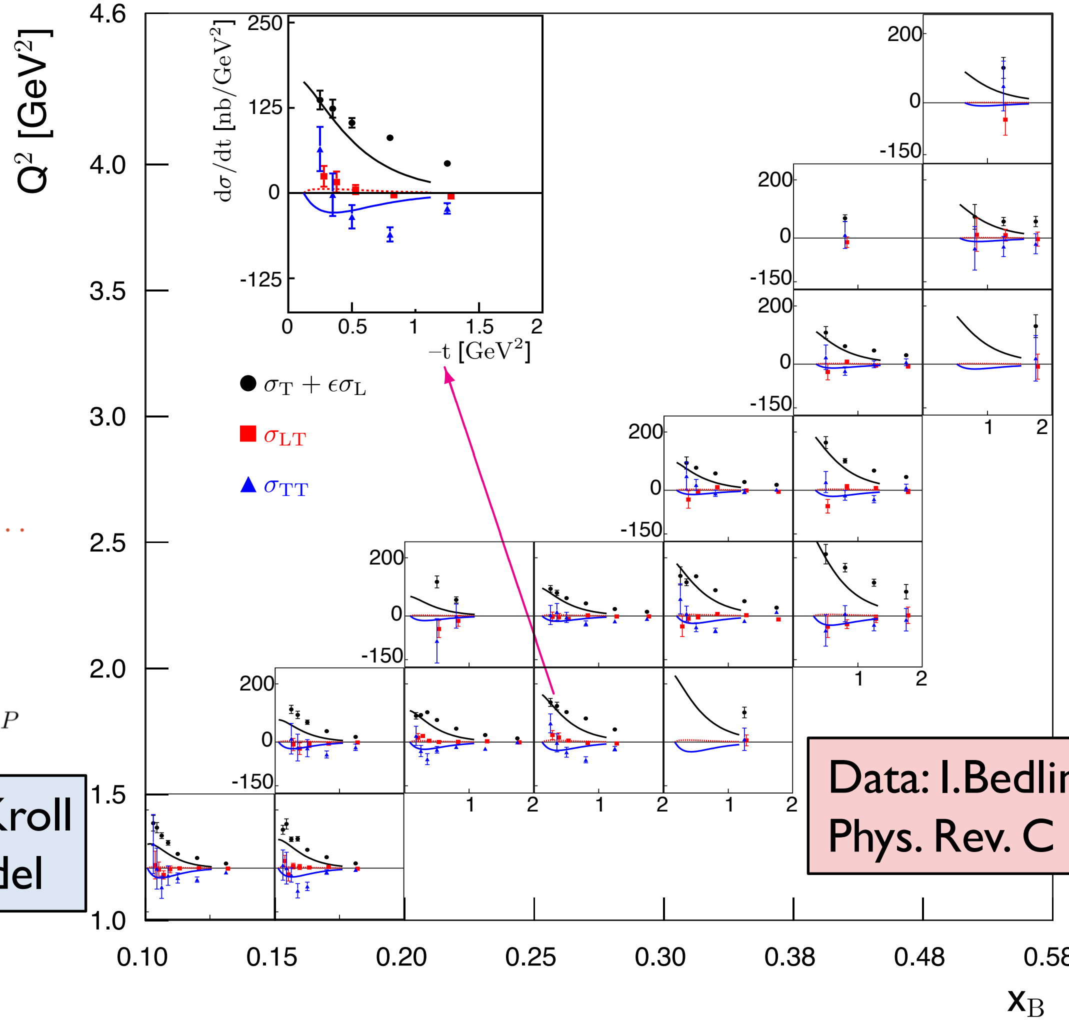
Curves: Goloskokov, Kroll
Transversity GPD model (2011)

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

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

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

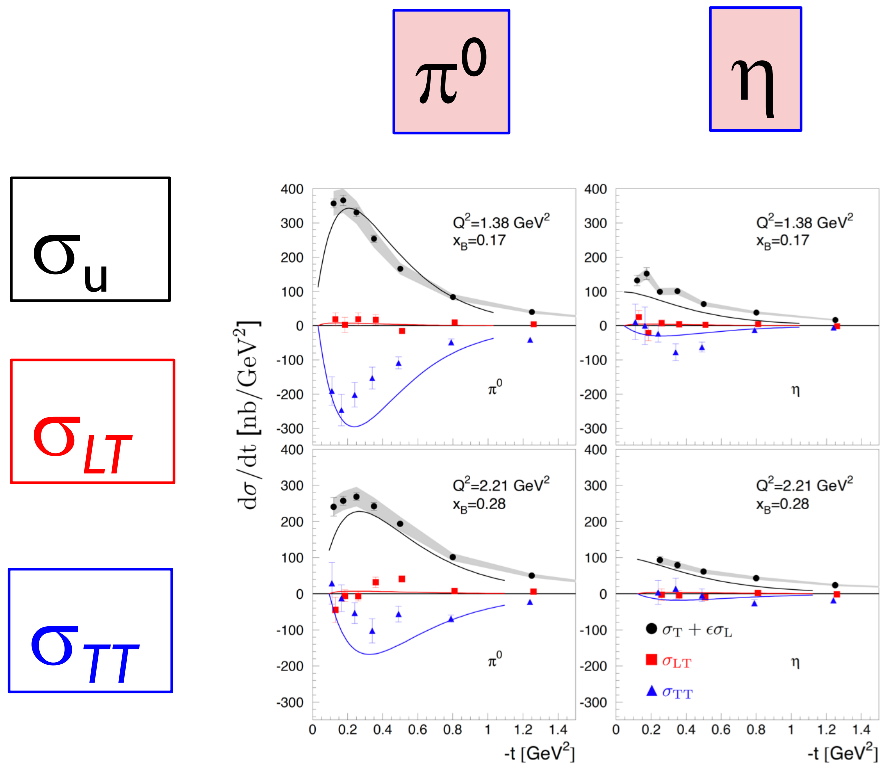




Curves: Goloskokov, Kroll
Transversity GPD model

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

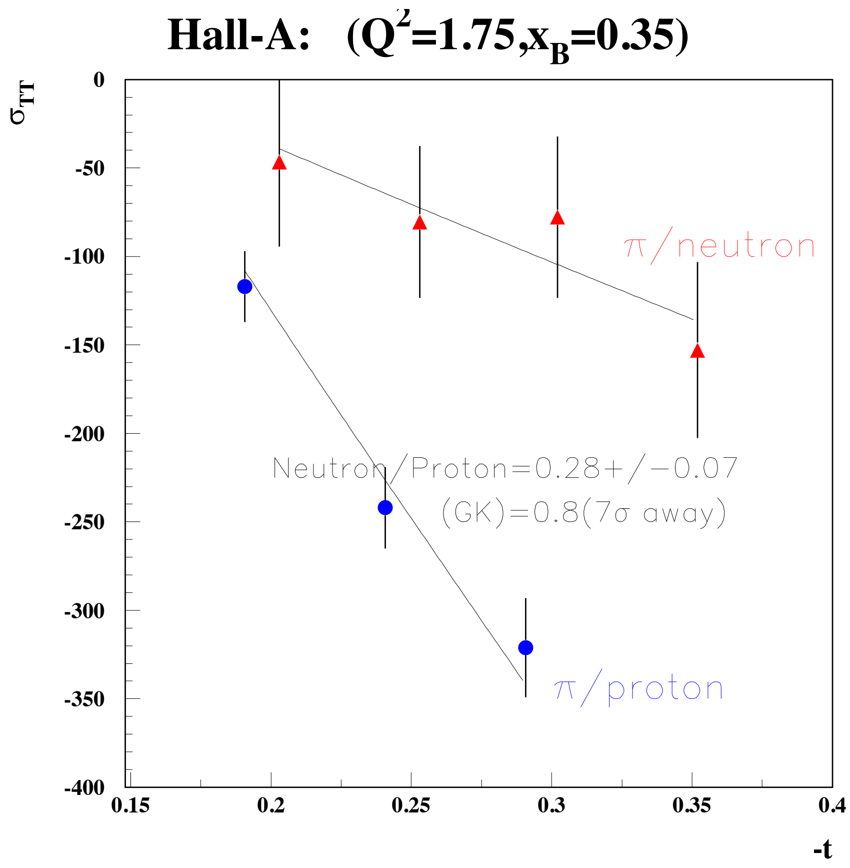
CLAS6 π^0/η Comparison



CLAS-Phys.Rev.C95(2017)

- σ_{TT} drops by a factor of 10
- The GK GPD model (curves) follows the experimental data

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



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

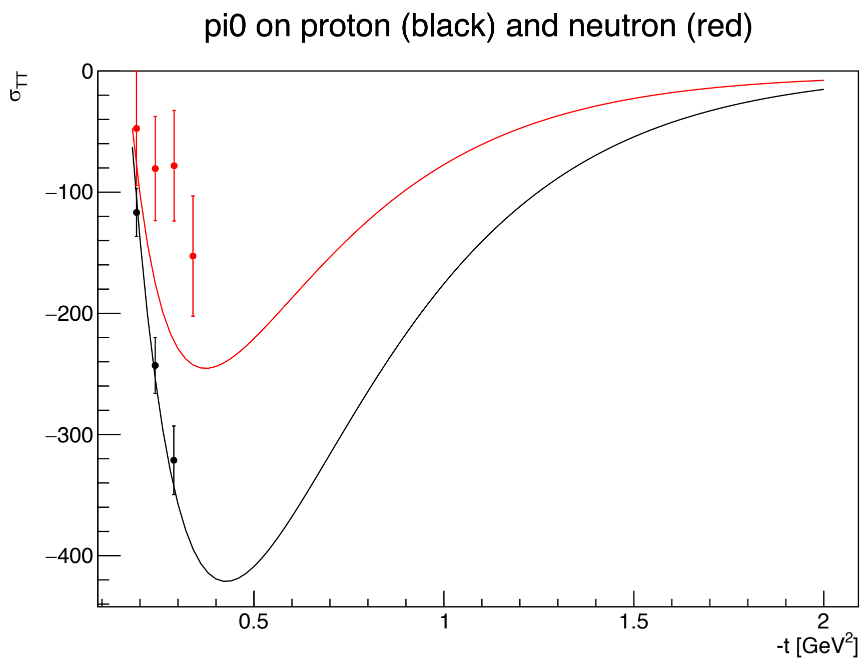
$$\bar{E}_T^{\pi/proton} = \frac{1}{3\sqrt{2}}(2\bar{E}_T^u + \bar{E}_T^d) \quad (1)$$

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

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

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

GK exact calculation of σ_{TT}



- Neutron/proton = 0.28
- GK model ~ 0.6
- Model parameters needed adjustment
- Global fit is in progress

$$\bar{E}_T^u(x, \chi = 0, t) = N^u \cdot e^{bt} \cdot x^{\alpha_0 + \alpha' t} \cdot (1-x)^4$$

$$\bar{E}_T^d(x, \chi = 0, t) = N^d \cdot e^{bt} \cdot x^{\alpha_0 + \alpha' t} \cdot (1-x)^5$$

Generalized Form Factors

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

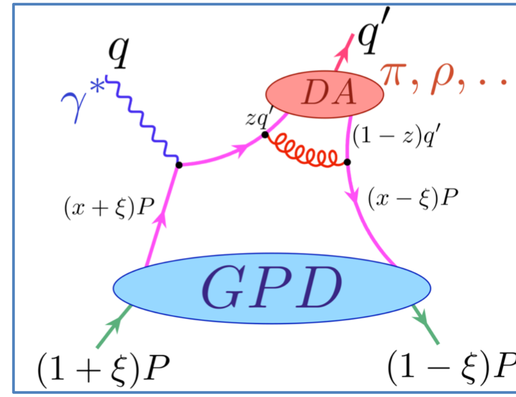
$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_P^2}{Q^8}\frac{t'}{16m^2}|\langle \bar{E}_T\rangle|^2$$

Goloskokov, Kroll
Transversity GPD model

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

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

- *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.



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

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

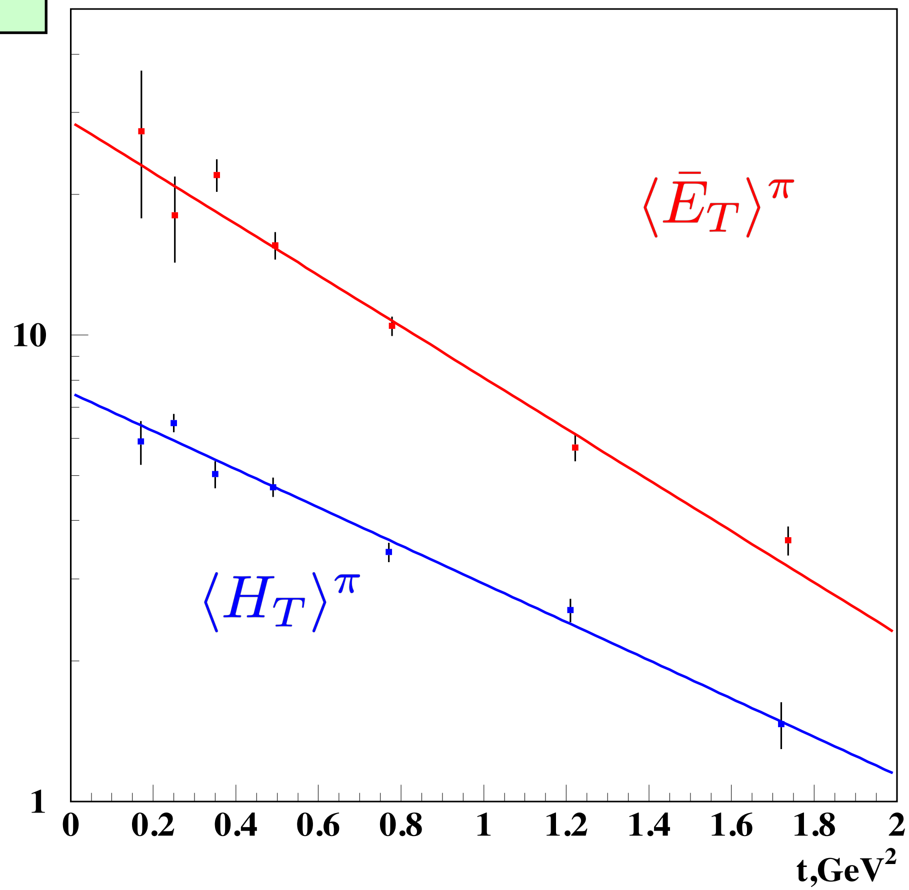
The brackets <F> denote the convolution of the elementary process with the GPD F (generalized form factors)

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

π^0 Generalized Form Factors

$$\frac{d<F>}{dt} \propto e^{bt}$$

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



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

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

VK, arXiv:1601.04367

Monte Carlo Generator

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

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

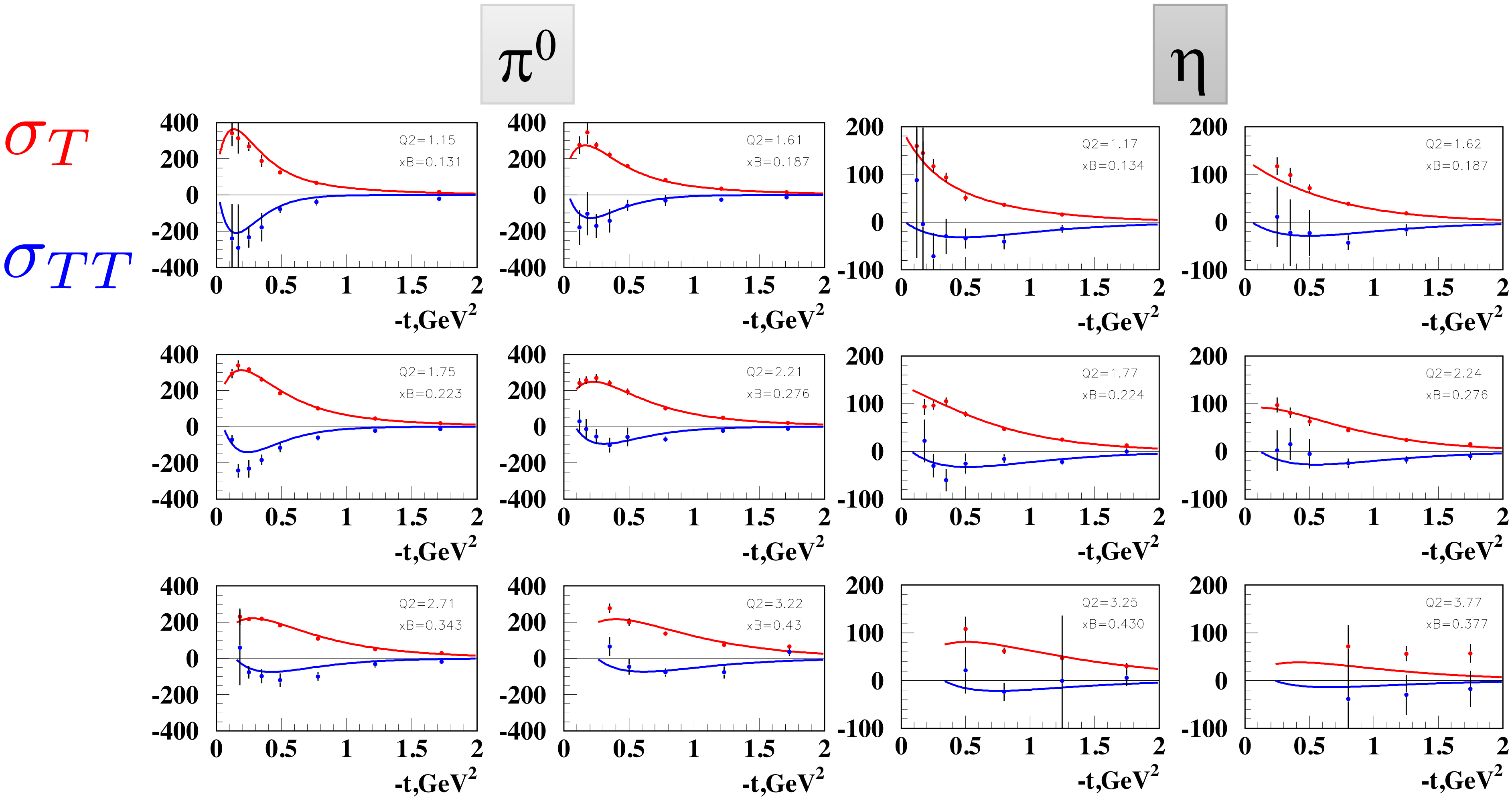
$$\sigma_{TT} = \frac{4\pi\alpha_e}{2\kappa}\frac{\mu_\pi^2}{Q^4}\frac{t'}{8m^2}|\langle \bar{E}_T\rangle|^2$$

$$\bar{E}_T(t, x_B, Q^2) = N_E \cdot e^{(\alpha_E + \beta_E \log(x_B))t} \cdot Q^{\gamma_E}$$

$$H_T(t, x_B, Q^2) = N_H \cdot e^{(\alpha_H + \beta_H \log(x_B))t} \cdot Q^{\gamma_H}$$

- t-slope parameter is a function of x_B
- Q^2 dependence reflects the dependence of the formfactors on Q^2
- The parameters were used in the fit of experimental observables – cross sections

Quality of the fit



COMPASS arXiv:1903.12030, 28 Mar,2019

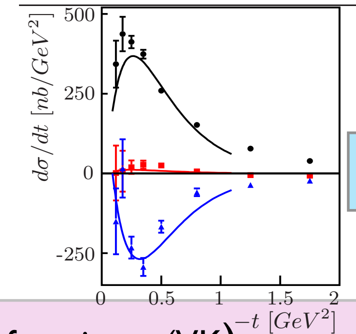
- 160 GeV/c polarized μ^+ and μ^- beams of the CERN SPS
- Data taken in 2012, within 4 weeks
- **$\langle Q2 \rangle = 2.0$ GeV^2**
- **$\langle xB \rangle = 0.093$**
- $\langle -t \rangle = 0.256$ GeV^2

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

COMPASS-Jlab comparison

- **$\langle Q^2 \rangle$=2.0 GeV^2**
- **$\langle x_B \rangle$=0.093**
- $\langle -t \rangle$=0.256 GeV^2
- **$\langle \nu \rangle$=12.8 GeV**

COMPASS data (5 points)

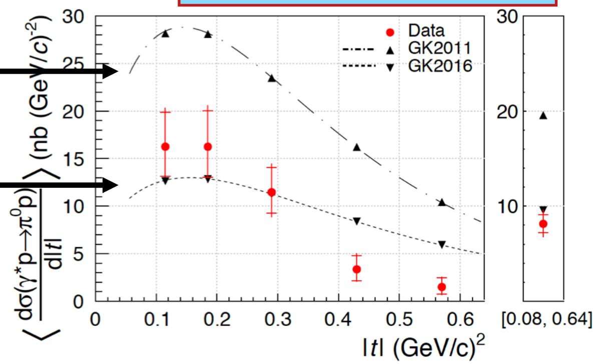


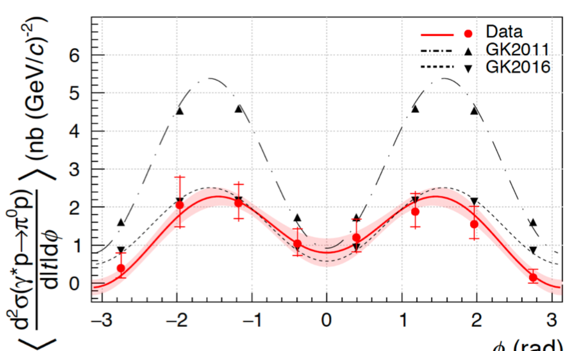
CLAS 2000 points

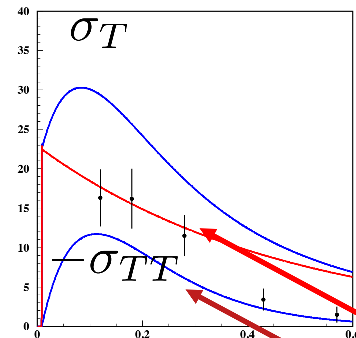
CLAS structure functions (VK)

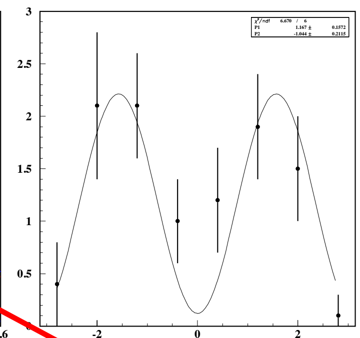
GK2011

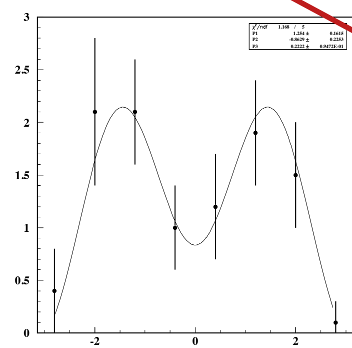
GK2016









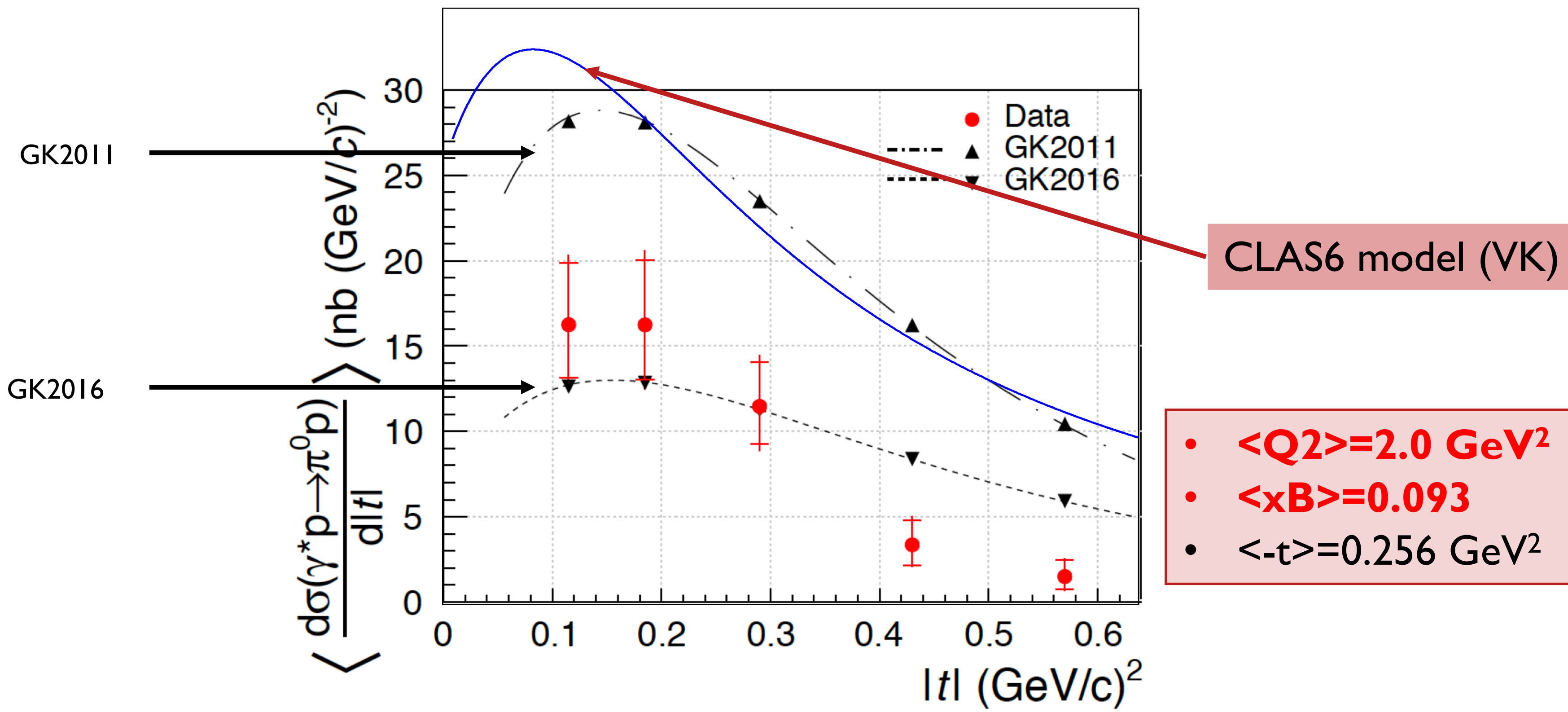


$\langle H_T \rangle$

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

- Factor of two difference between GK2011 and GK2016
- Factor of two difference between COMPAS and CLAS

GK2011 and CLAS6 model



- **$\langle Q2 \rangle = 2.0$ GeV^2**
- **$\langle xB \rangle = 0.093$**
- $\langle -t \rangle = 0.256$ GeV^2

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

Flavor Decomposition

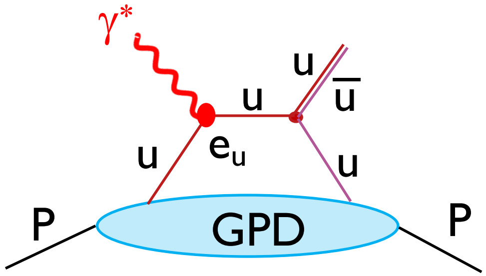
$$\bar{E}_T^{\pi/proton} = \frac{1}{3\sqrt{2}}(2\bar{E}_T^u + \bar{E}_T^d)$$

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

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

Handbag graph for π^0 electroproduction

$$\left|\pi^0\right\rangle = \frac{\left|u\bar{u}\right\rangle - \left|d\bar{d}\right\rangle}{\sqrt{2}}$$



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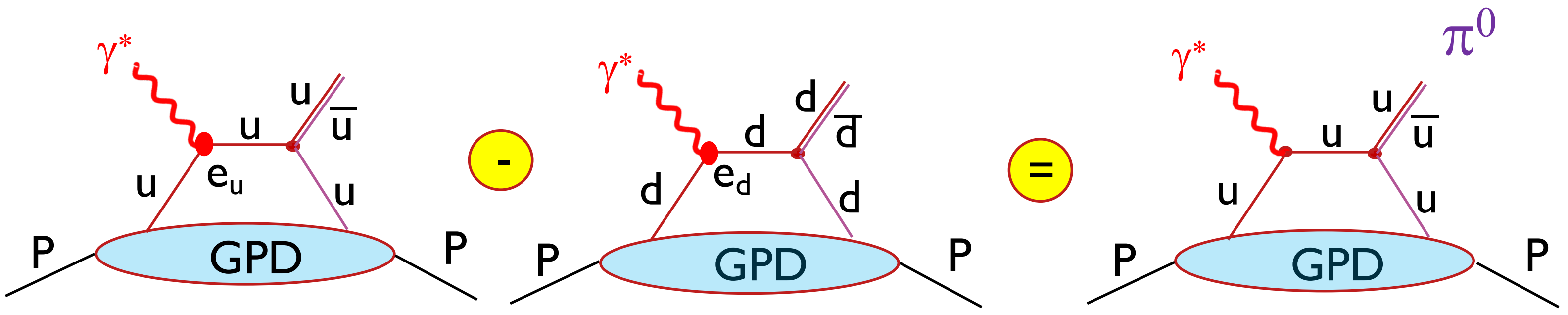

$$\bar{E}_T^{\pi} = \frac{1}{\sqrt{2}}(e_u \bar{E}_T^u - e_d \bar{E}_T^d) = \frac{1}{3\sqrt{2}}(2\bar{E}_T^u + \bar{E}_T^d)$$

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

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

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

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

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

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

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1.45

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$$\bar{E}_T^{\eta/proton} = \frac{1.45}{3\sqrt{6}}(2\bar{E}_T^u - \bar{E}_T^d - 2\cancel{\bar{E}_T^s}) \quad (3)$$

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

So, the contribution from sea quarks is cancelled out.

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$\bar{E}_T(x,t,\xi)$

Global fit

status report

Data

- CLAS π^0/η
- Hall-A π^0
- $\bar{E}_T(x,t,\xi)$ parameters only

- Fit *ONLY* σ_{TT} data

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

Goloskokov-Kroll GPDs Model

$$\bar{E}_T^u(x,t,\xi) = N^u \cdot e^{b^u t} \sum_{j=0}^{2} c_j^u \cdot \mathcal{D}(\frac{j}{2}, x, \xi)$$

$$\bar{E}_T^d(x,t,\xi) = N^d \cdot e^{b^d t} \sum_{j=0}^{4} c_j^d \cdot \mathcal{D}(\frac{j}{2}, x, \xi)$$

$$\mathcal{D}(i,x,\xi) = \frac{3}{2\xi^3(1+i-k)(2+i-k)(3+i-k)}\{(\xi^2 - x)\left(\left(\frac{x+\xi}{1+\xi}\right)^{2+i-k} - \left(\frac{x-\xi}{1+-xi}\right)^{2+i-k}\right) +\xi(1-x)(2+i-k)\left(\left(\frac{x+\xi}{1+\xi}\right)^{2+i-k} + \left(\frac{x-\xi}{1+-xi}\right)^{2+i-k}\right)\}$$

$$\mathcal{D}(i,x,\xi=0) = x^{i-k}(1-x)^3$$

$$k = \alpha_0 + \alpha' t$$

clas

ξ=0 Limit

$$\bar{E}_T^u(x,t,\xi) = N^u \cdot e^{b^u t} \sum_{j=0}^{2} c_j^u \cdot \mathcal{D}(\frac{j}{2}, x, \xi)$$

$$\bar{E}_T^d(x,t,\xi) = N^d \cdot e^{b^d t} \sum_{j=0}^{4} c_j^d \cdot \mathcal{D}(\frac{j}{2}, x, \xi)$$

$\xi \to 0$

$$\bar{E}_T^u(x,t,\xi=0) = N^u \cdot x^{-\alpha_0^u}(1-x)^4 e^{(b^u - \alpha'^u \ln(x))t}$$

$$\bar{E}_T^d(x,t,\xi=0) = N^d \cdot x^{-\alpha_0^d}(1-x)^5 e^{(b^d - \alpha'^u \ln(x))t}$$

clas

ξ=0 Limit

$$\bar{E}_T^u(x,t,\xi) = N^u \cdot e^{b^u t} \sum_{j=0}^{2} c_j^u \cdot \mathcal{D}(\frac{j}{2}, x, \xi)$$

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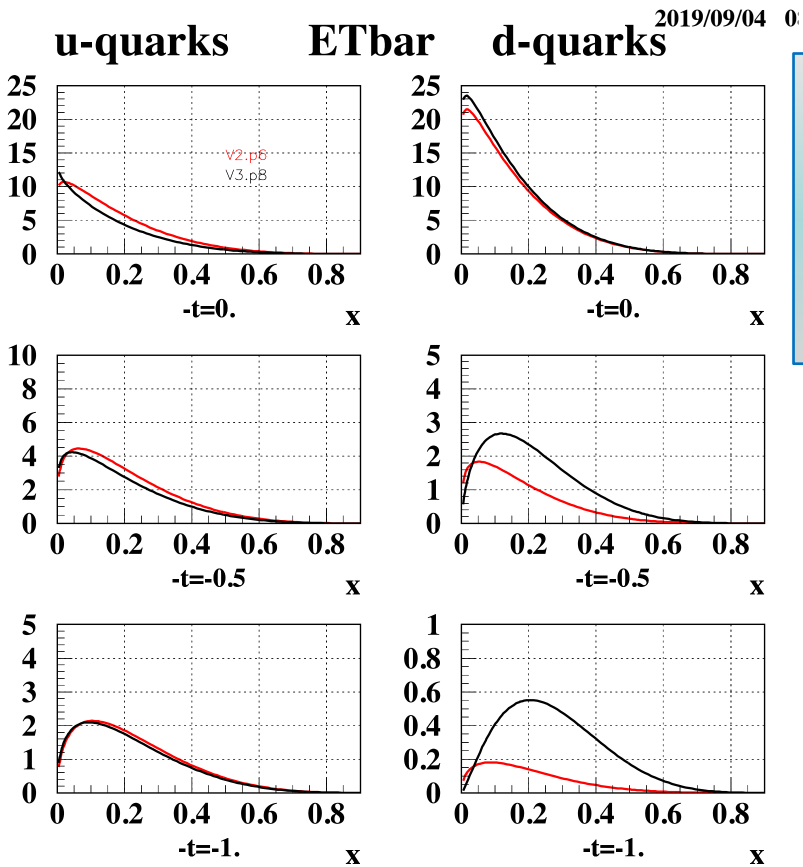
$$\bar{E}_T^u(x,t,\xi=0) = N^u \cdot x^{-\alpha_0^u}(1-x)^4 e^{(b^u - \alpha'^u \ln(x))t}$$

$$\bar{E}_T^d(x,t,\xi=0) = N^d \cdot x^{-\alpha_0^d}(1-x)^5 e^{(b^d - \alpha'^u \ln(x))t}$$

$\bar{E}_T(x, t, \xi = 0)$ x-distributions, -t=0,0.5,1 GeV^2



- α_0 and α' are the same for u and d quarks
- α_0 and α' for u and d quarks are free parameters

Plan moving forward

- Two sets of data were used for a moment: CLAS (π^0 and η) and Hall-A (π^0 only) out of proton
- Hall-A published π^0 structure functions for neutron
- COMPASS released π^0 muon electroproduction out of proton
- The problem with Hall-A neutron and COMPASS data is connected with the fact that there is only one kinematic point (Q^2,x_B) published
- Neutron data will help for the flavor separation and COMPASS to fix energy dependence of GPDs

What $\bar{E}_T(x, t, \xi)$ will tell us about the nucleon structure?

The Fourier Transform of Generalized Parton Distribution

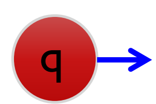
- The Fourier transforms of GPDs at $\xi = 0$ describe the distribution of partons in the transverse plane (M. Burkardt, 2002)
- It was shown that they satisfy positivity constraints which justify their physical interpretation as a probability density
- **H** is related to the impact parameter distribution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

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

The Density of Transversely Polarized Quarks in an Unpolarized Proton

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

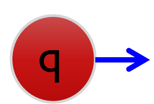
$$\delta(x,\vec{b}) = \frac{1}{2}\left[H(x,\vec{b}) - \frac{b_y}{m}\frac{\partial}{\partial b^2}\bar{E}_T(x,\vec{b})\right]$$



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

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



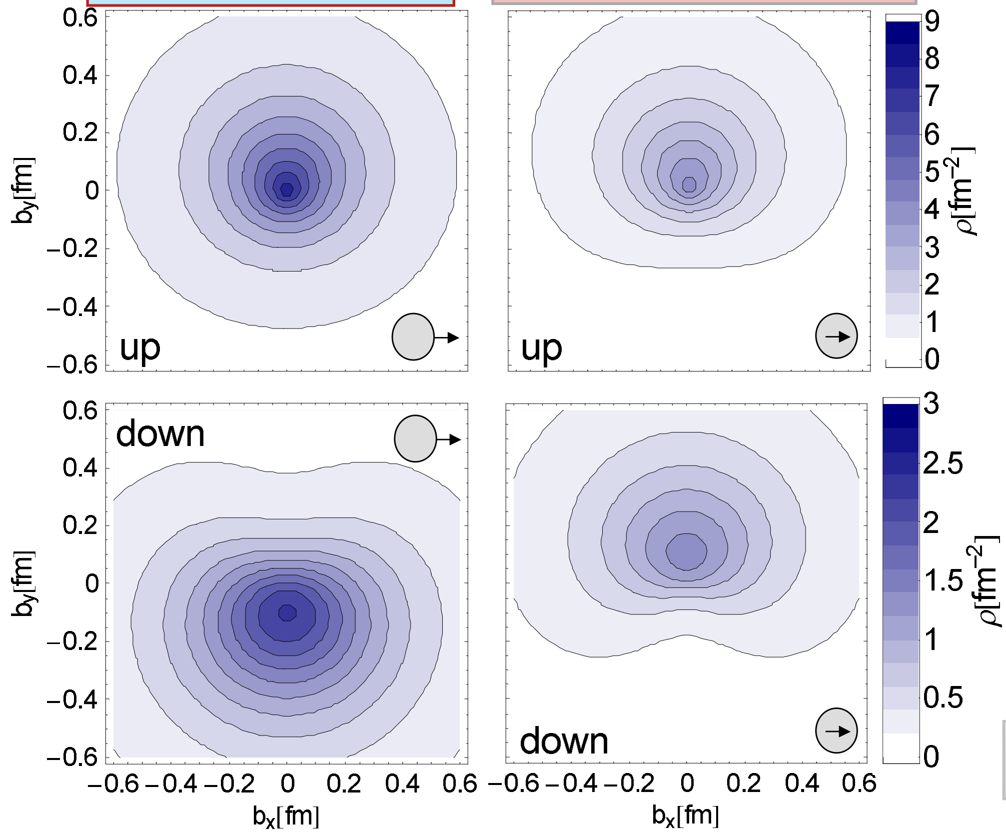
Integrated over *x* Transverse Densities for u and d Quarks in the Proton

Polarized proton | Unpolarized proton

u quarks

d quarks

Strong distortions for unpolarized quarks in transversely polarized proton



Strong distortions for transversely polarized quarks in an unpolarized proton

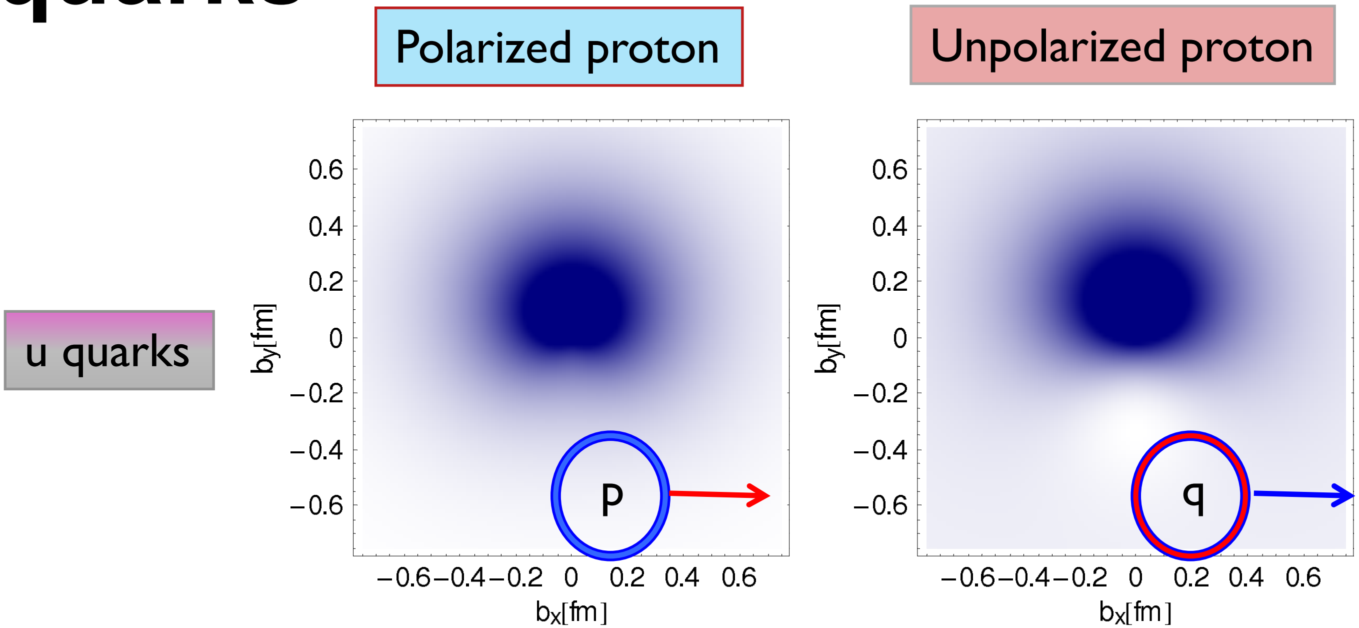
Lattice calculations

Controlled by E

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

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

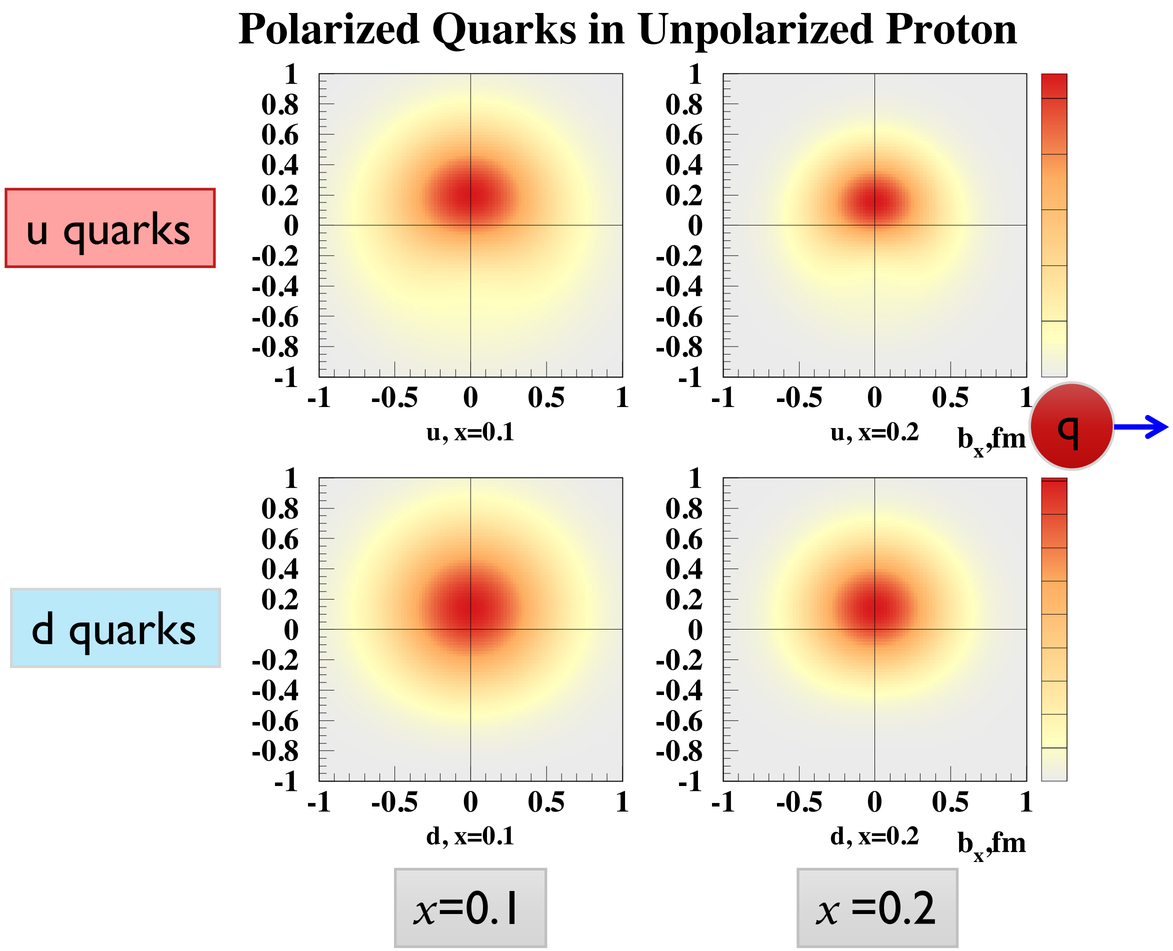
GPD model: integrated over *x* Impact Parameter Density for u-quarks



- **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.

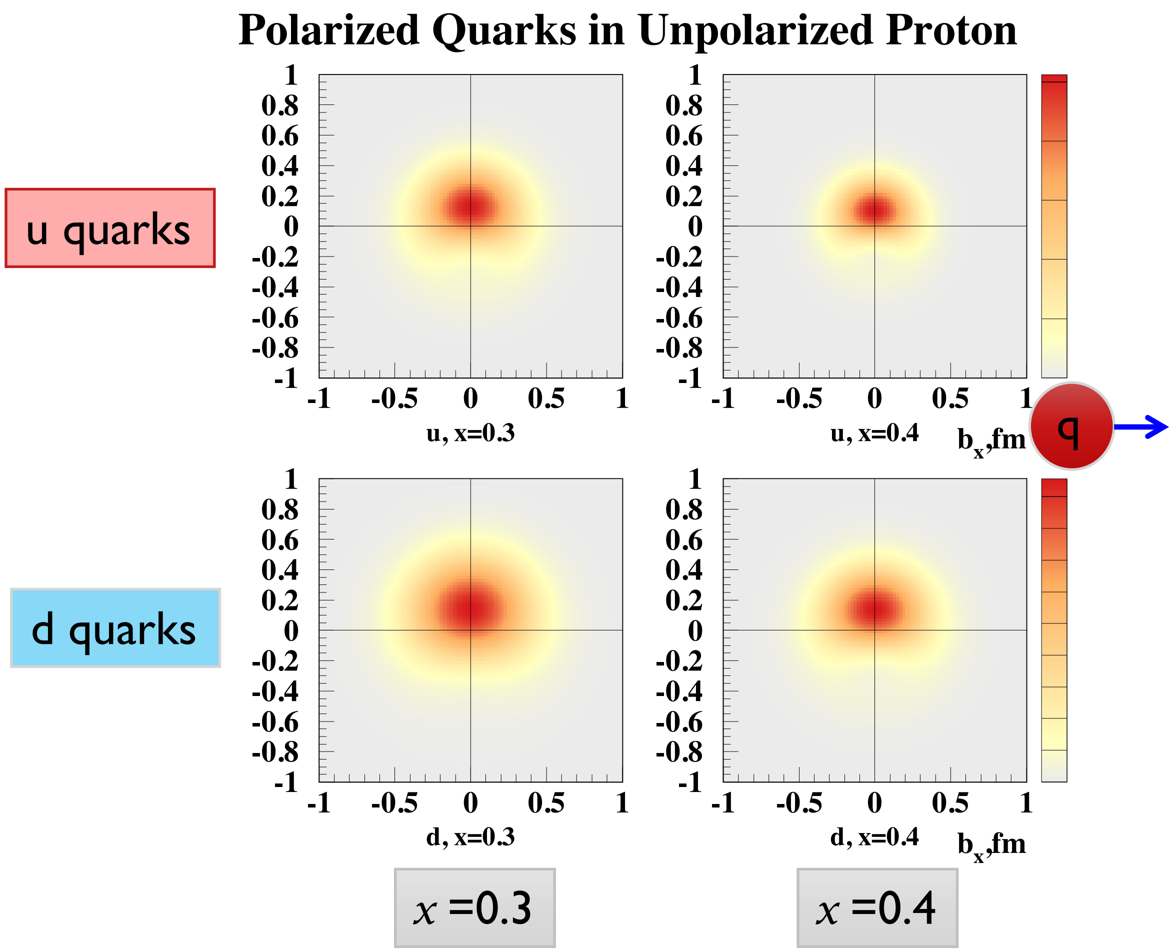
M. Diehl and Ph Hagler (2005) GPD model with "some reasonable " parameters.

Transverse Densities for u and d Quarks in the Proton

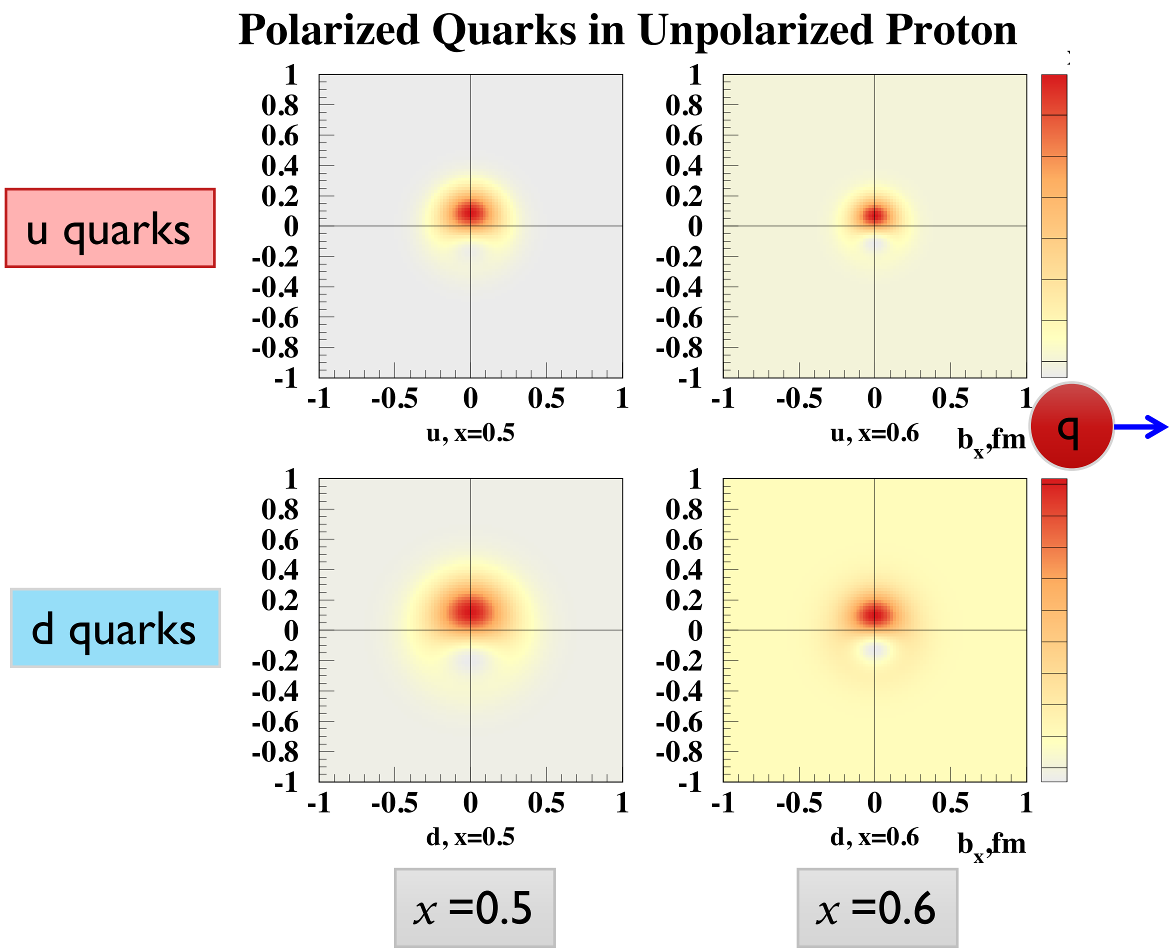


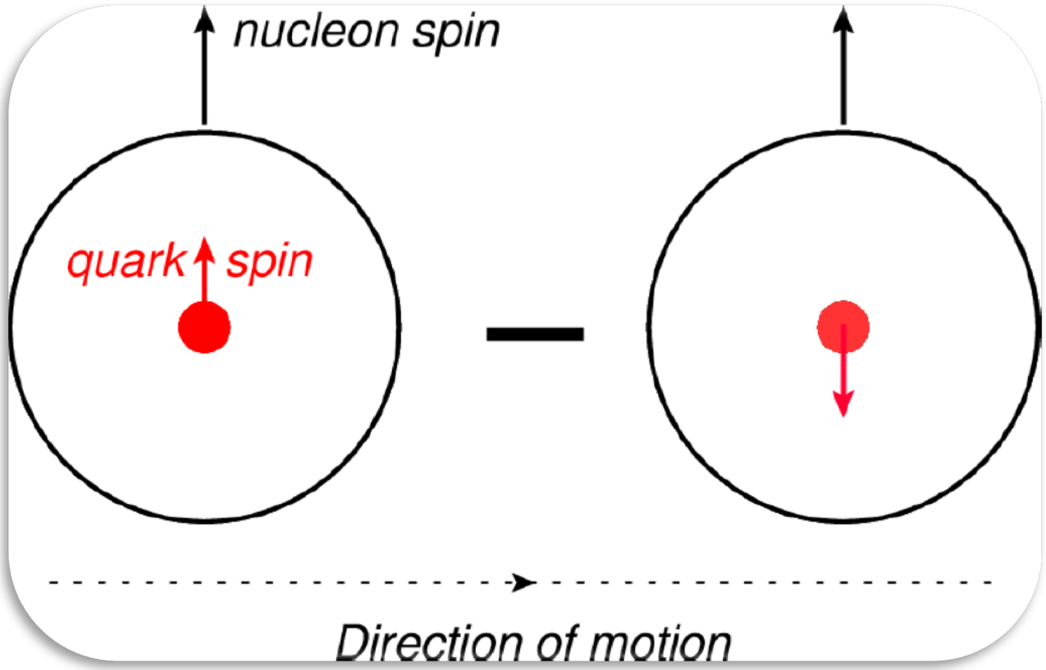
Note distortions for transversely polarized u and d quarks.

Transverse Densities for u and d Quarks in the Proton



Transverse Densities for u and d Quarks in the Proton





Proton's Tensor Charge

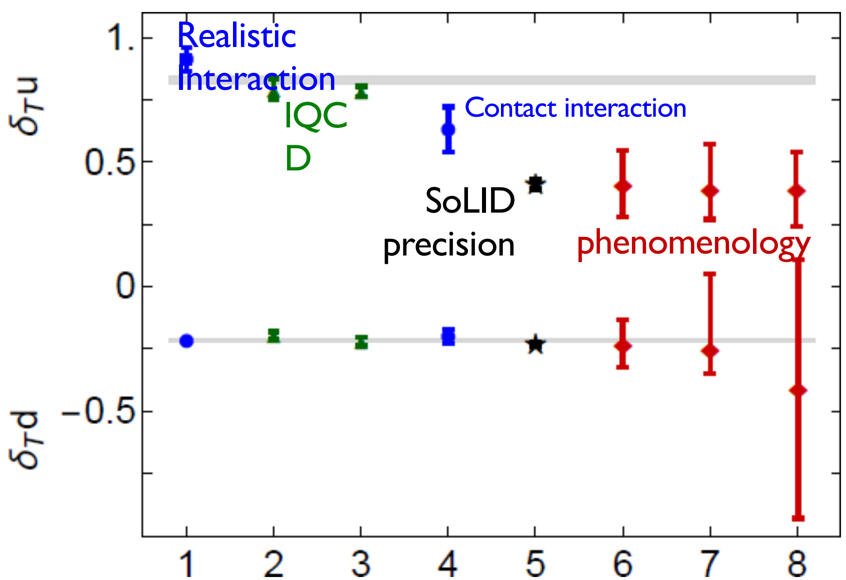
Proton tensor charges from a Poincaré-covariant Faddeev equation, Qing-Wu Wang, S.-X. Qin, C.D. Roberts and S. M. Schmidt, arXiv:1806.01287 [nucl-th], Phys. Rev. D **98** (2018) 054019/1-10

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

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

$$g_T^{(1)} = 1.130^{(42)}_{(47)}\,, \qquad g_T^{(0)} = 0.694^{(42)}_{(47)}$$

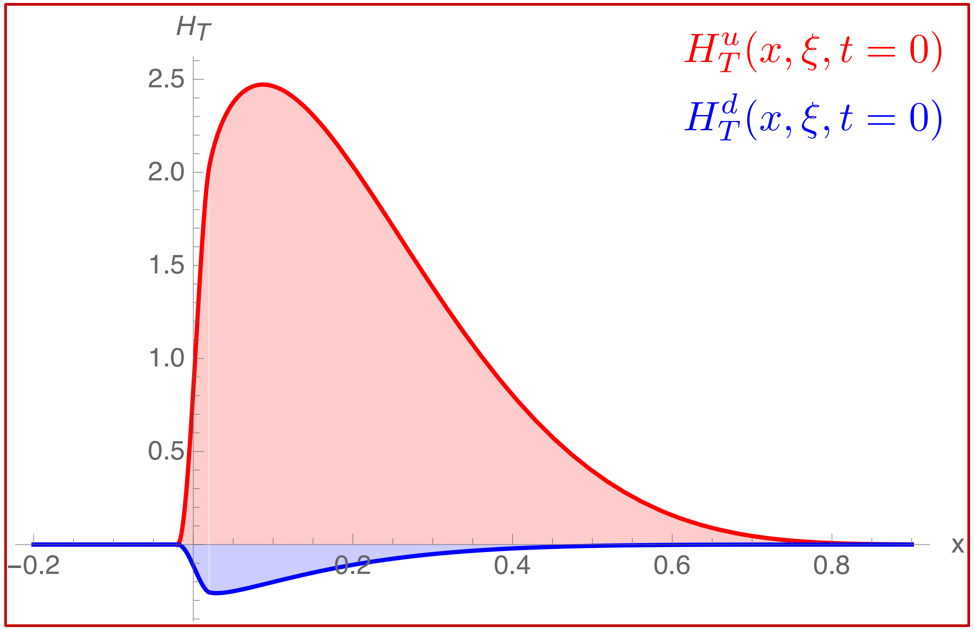


$$\overline{\delta_T u} = 0.803(17)\,,\ \overline{\delta_T d} = -0.216(4)$$

Proton Tensor Charge

$$\delta_T^u = \int dx H_T^u(x,\xi,t=0) = \ 0.830$$

$$\delta_T^d = \int dx H_T^d(x,\xi,t=0) = -0.052$$

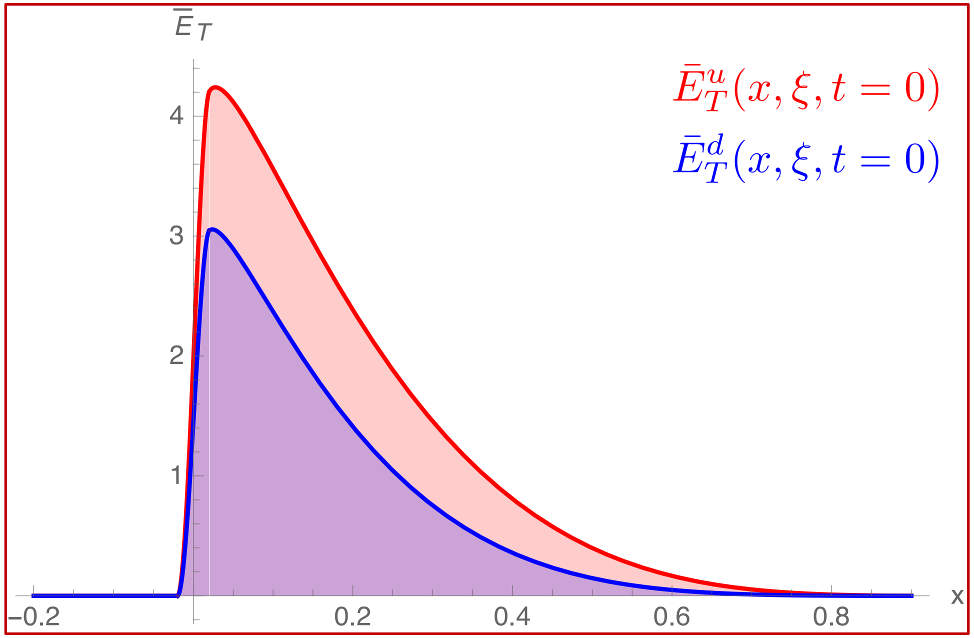


Theory average $\overline{\delta_T u} = 0.803(17)\,,\ \overline{\delta_T d} = -0.216(4)$

Proton Anomalous Tensor Magnetic Moment

$$\kappa_T^u = \int dx \bar{E}_T^u(x,\xi,t=0) = 2.07$$

$$\kappa_T^d = \int dx \bar{E}^d(x,\xi,t=0) = 1.35$$



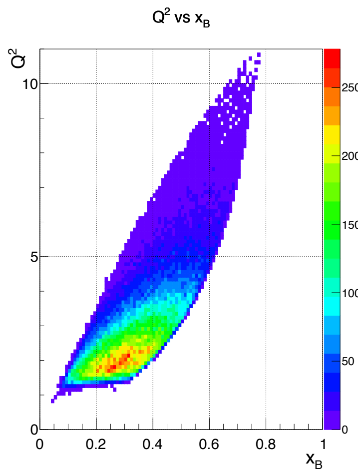
Note the same signs of $\bar{E}_T^u$ and $\bar{E}_T^d$

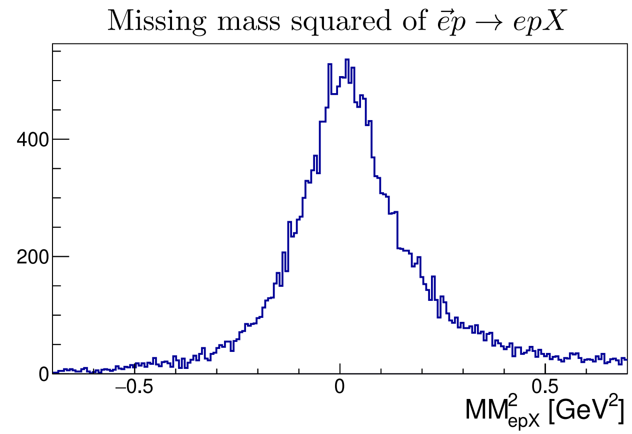
Chiral soliton model : $\kappa^u_T = 3.56$, $\kappa^d_T = 1.83$

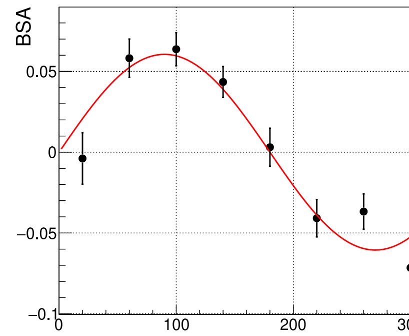
Lattice: $\kappa^u_T = 2.07$, $\kappa^d_T = 1.35$ (used as input for the GK model)

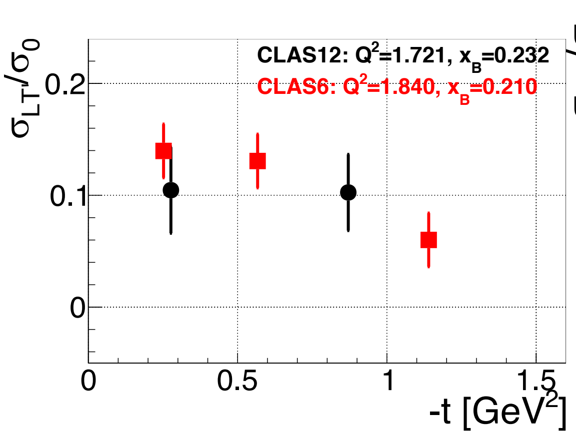
CLAS12 BSA

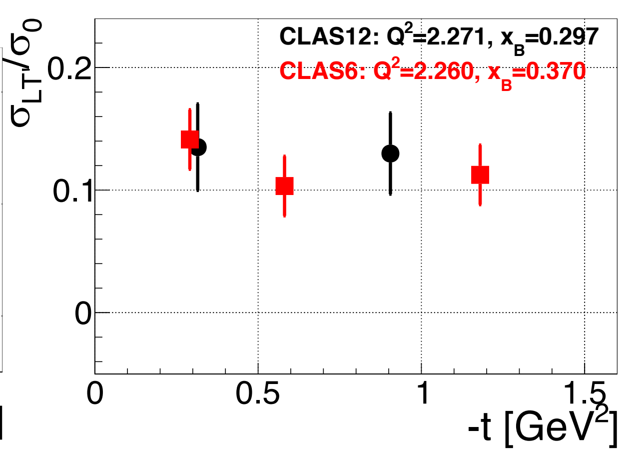
$$\gamma^* p \rightarrow p\pi^0$$

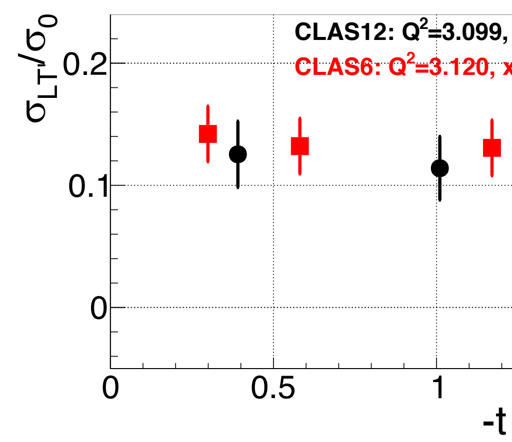












A. K

Future developments

- Asymmetries, Cross section at different beam energies: RGA, RGB, RGK

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

- Asymmetries:
  - $\mathcal{A}_{LU}$ − *beam spin*
  - $\mathcal{A}_{UL}$ − *target spin*
  - $\mathcal{A}_{LL}$ − *beam target*

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 brand new CLAS12 detector successfully took data with proton and deuteron targets data with 10.6, 10.2, 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.