Study of Chiral-Odd GPDs using Deeply Virtual Pseudoscalar Meson Electroproduction measurements at Jefferson Lab

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Strong QCD from Hardon Structure Experiments Workshop
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Generalized Parton Distributions (GPDs)

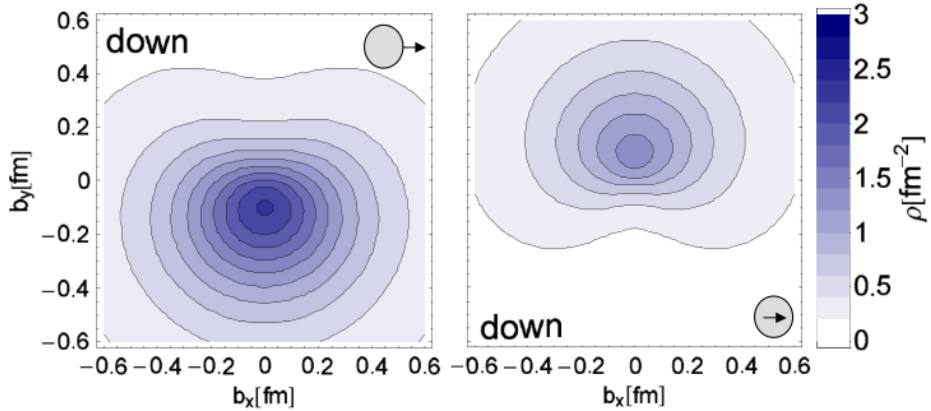
Nucleon polarization	Quark polarization: U	Quark polarization: L	Quark polarization: T
U	H		$\bar{E}_T$
L		$\tilde{H}$	
T	E		H_T, $\tilde{H}_T$

Chiral-odd GPD results:

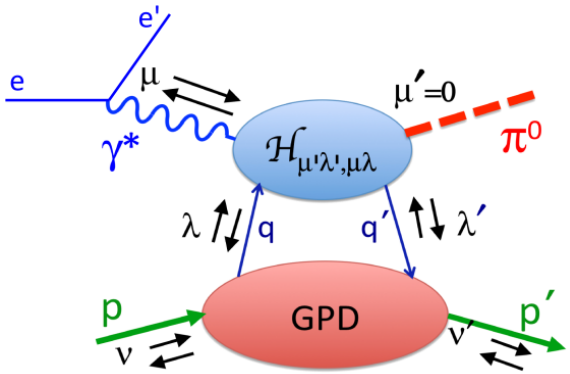
- Deeply virtual meson production
- Lattice QCD by Göckeler *et al*

Chiral even GPDs:

- DVCS on unpolarized and polarized targets with polarized beam by HERMES, JLAB and COMPASS



GPDs in deeply virtual exclusive reactions

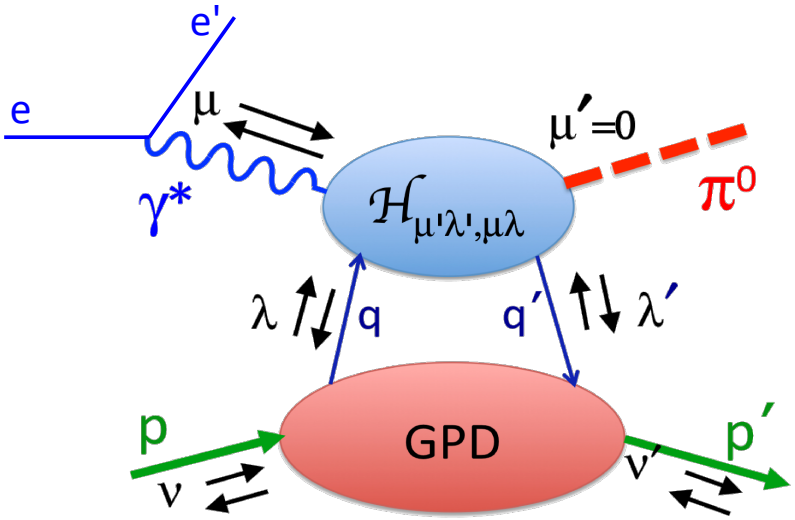


- $\langle F \rangle = \sum_\lambda \int_{-1}^{1} dx \mathcal{H}_{0\lambda,\mu\lambda}\left(x, \xi, Q^2, t\right) F\left(x, \xi, t\right)$

Generalized Form Factor (GFF) $\langle F \rangle$ is a convolution of hard subprocess with GPD F

- 4 parton helicity conserving (chiral even) GPDs: H, $\tilde{H}$, E, $\tilde{E}$
- 4 parton helicity flip (chiral odd) GPDs: H_T, $\tilde{H}_T$, E_T, $\tilde{E}_T$
- functions of three kinematic variables: x, ξ and t

GPDs in deeply virtual exclusive reactions



$$\langle F \rangle = \sum_{\lambda} \int_{-1}^{1} dx \mathcal{H}_{0\lambda,\mu\lambda}(x,\xi,Q^2,t) F(x,\xi,t)$$

Generalized Form Factor

$$Q^2 = -(e-e')^2$$

$$x_B = \frac{Q^2}{2m\nu}$$

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

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

$$\nu = E_e - E_{e'}$$

- **Quark flavor decomposition:**

$$F_i^{\pi^0} = \frac{(e_u F_i^u - e_d F_i^d)}{\sqrt{2}} \qquad F_{ip\to\Lambda} = -\frac{(2F_i^u - F_i^d)}{\sqrt{6}}$$

$$F_i^{\eta} = \frac{(e_u F_i^u + e_d F_i^d)}{\sqrt{6}} \qquad F_{ip\to\Sigma^0} = -\frac{F_i^d}{\sqrt{2}}$$

- **Flavor ratios: cancellation of higher twist effects**

$$\pi^0/\eta, \cdots$$

Goldstein-Gonzalez-Liuti model

Chiral-even GPDs parametrization

recursive fit by imposing constraints from:

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,‡]
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[2]*Department of Physics, University of Virginia, Charlottesville, Virginia 22901, USA*
(Received 16 February 2011; published 5 August 2011)

DIS experimental results → elastic form factors → DVCS data

Evaluation of chiral-odd GPDs through the linear relations with chiral even GPDs within GGL model:

$$\widetilde{H}_T = -\frac{1}{F}\left(E - \frac{\zeta}{2}\widetilde{E}\right)$$

$$E_T = \frac{(1-\zeta/2)^2}{1-\zeta}\left[E - 2\widetilde{H}_T - (\frac{\zeta/2}{1-\zeta/2})^2\widetilde{E}\right]$$

$$\widetilde{E}_T = \frac{\zeta/2(1-\zeta/2)}{1-\zeta}\left[E - 2\widetilde{H}_T - \widetilde{E}\right]$$

$$H_T = \frac{H+\widetilde{H}}{2} - \frac{\zeta^2/4}{1-\zeta}\frac{E+\widetilde{E}}{2} - \frac{\zeta^2/4}{(1-\zeta/2)(1-\zeta)}E_T + \frac{\zeta/4(1-\zeta/2)}{1-\zeta}\widetilde{E}_T - \frac{t_0-t}{4M^2}\frac{1}{F}\left(E - \frac{\zeta}{2}\widetilde{E}\right)$$

Goloskokov-Kroll model

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]

GPDs parametrization:

H_T

tensor charge: T.Ledwig, A.Silva, H.C. Kim

$$\int dx H_T(x,\xi,t)$$

transversity PDF: M.Anselmino

$$H_T(x,\xi=0,t=0)=h_1$$

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

Lattice QCD: M.Gockeler

$\bar{E}_T$ moments

UNPOLARIZED STRUCTURE FUNCTIONS:

$$\sigma_L \sim \left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2 \mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$$

$$\sigma_T \sim \left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle E_T\rangle\right|^2\right]$$

$$\sigma_{TT} \sim \left|\langle\bar{E}_T\rangle\right|^2$$

POLARIZED OBSERVABLES:

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

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

$$A_{LL}^{\cos 0\phi}\sigma_0 \sim \left|\langle H_T\rangle\right|^2$$

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

Constraining chiral-odd GPDs with JLab π^0 and η data

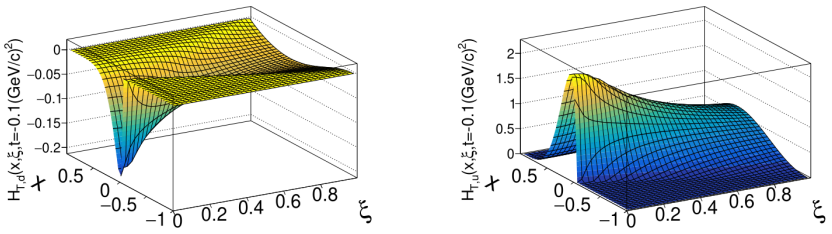
CLAS6 π^0 and η on proton:

- π^0: σ_0, $\sigma_{\mathbf{TT}}$, σ_{LT} at 95 $\{Q^2, x_B, -t\}$ kinematic bins, 17 $\{Q^2, x_B\}$ bins
- η: σ_0, $\sigma_{\mathbf{TT}}$, σ_{LT} at 68 $\{Q^2, x_B, -t\}$ kinematic bins, 16 $\{Q^2, x_B\}$ bins

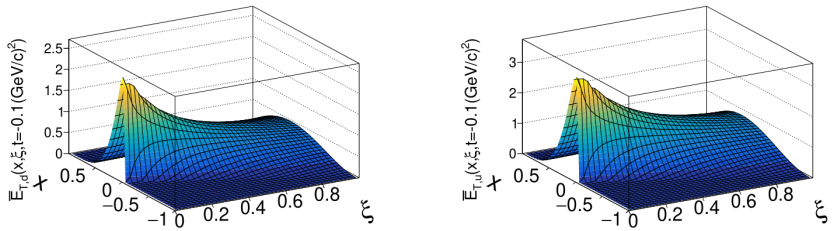
Hall A π^0 on proton and neutron:

- π^0 on proton: σ_T, σ_L, $\sigma_{\mathbf{TT}}$, σ_{LT} at 14 $\{Q^2, x_B, -t\}$ kinematic bins, 2 $\{Q^2, x_B\}$ bins
- π^0 on neutron: σ_T, σ_L, $\sigma_{\mathbf{TT}}$, σ_{LT} at 4 $\{Q^2, x_B, -t\}$ kinematic bins, 1 $\{Q^2, x_B\}$ bins

H_T GPDs for u and d quarks

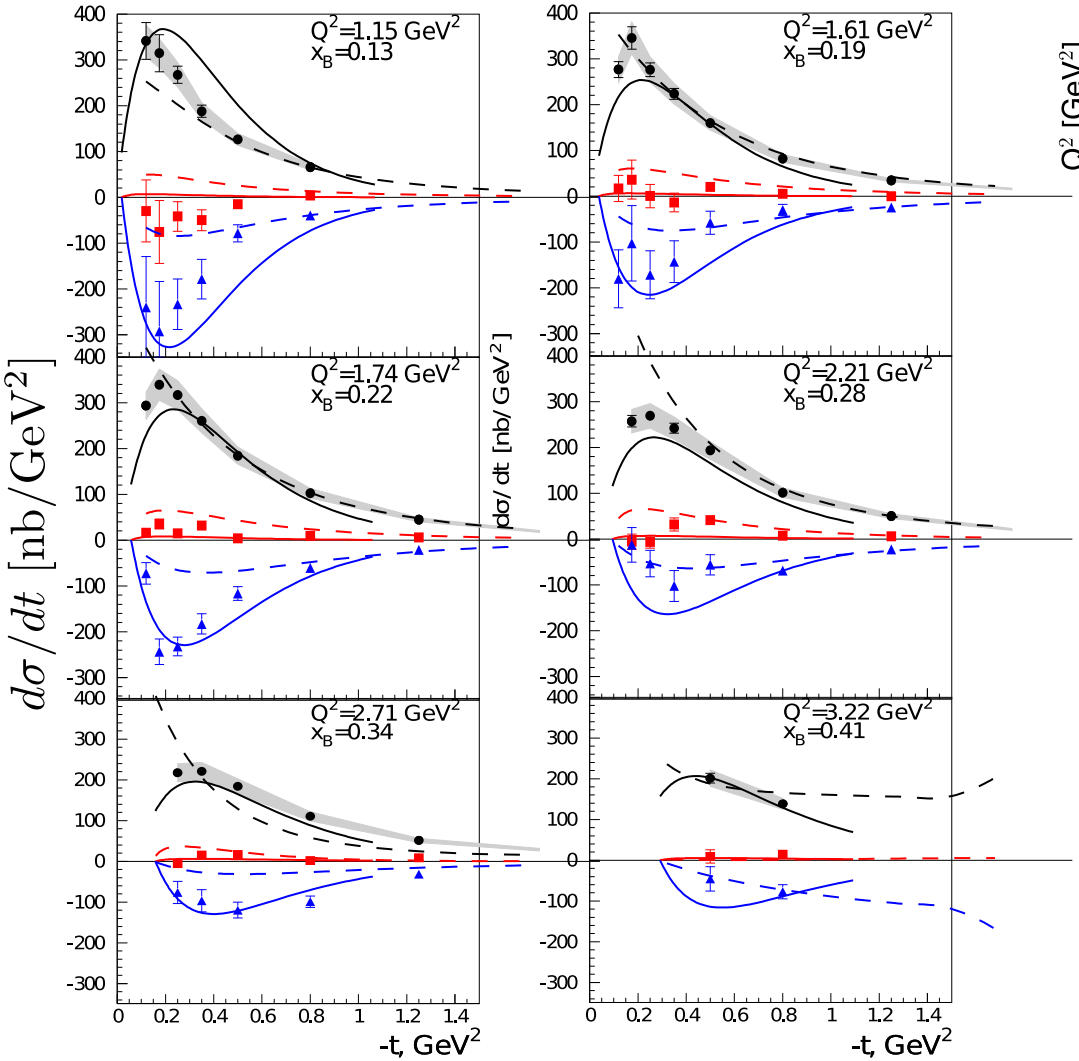


$\bar{E}_T$ GPDs for u and d quarks



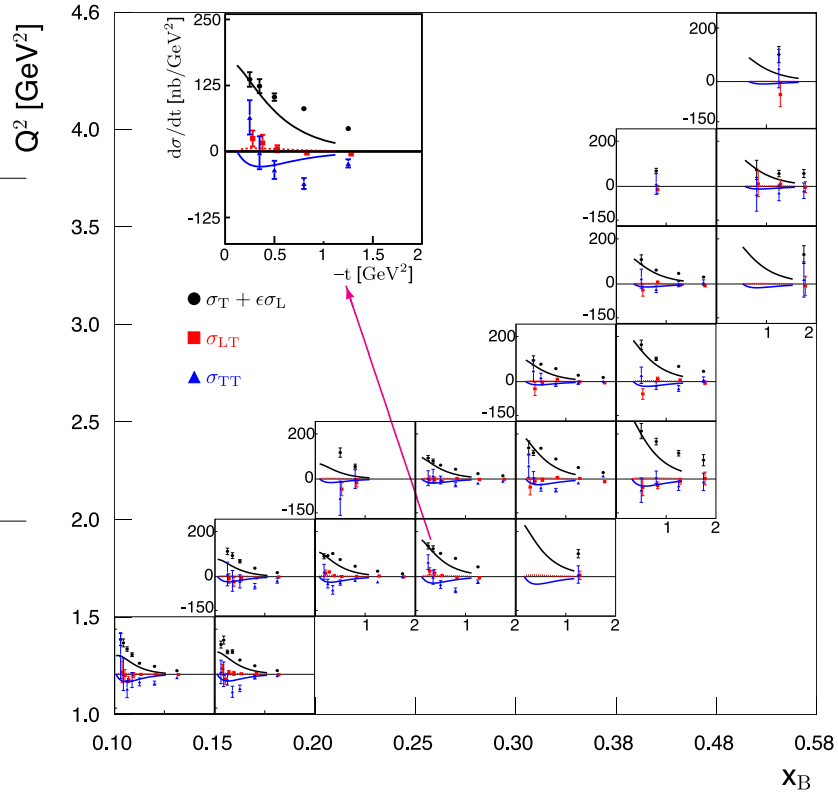
π^0/η structure functions from CLAS

π^0 electroproduction



PRL109:112001 (2012) I. Bedlinskiy et al. (CLAS collaboration)

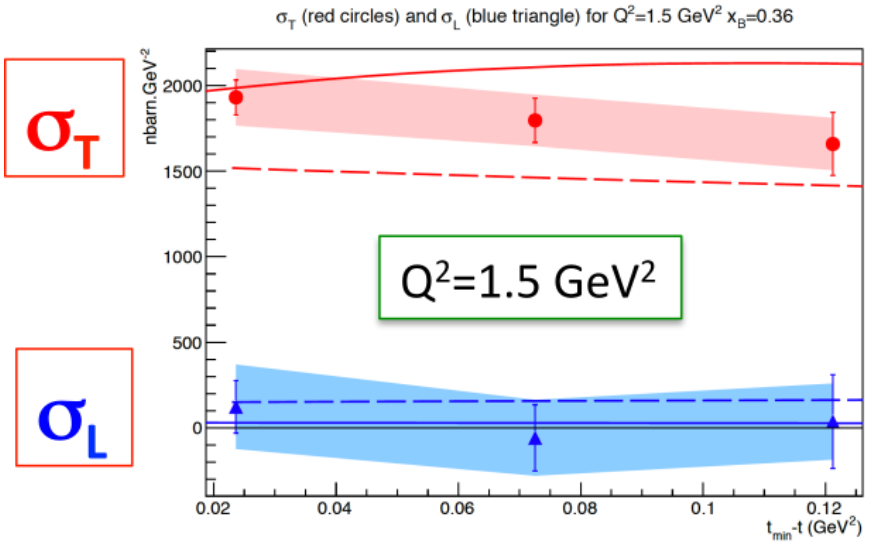
η electroproduction

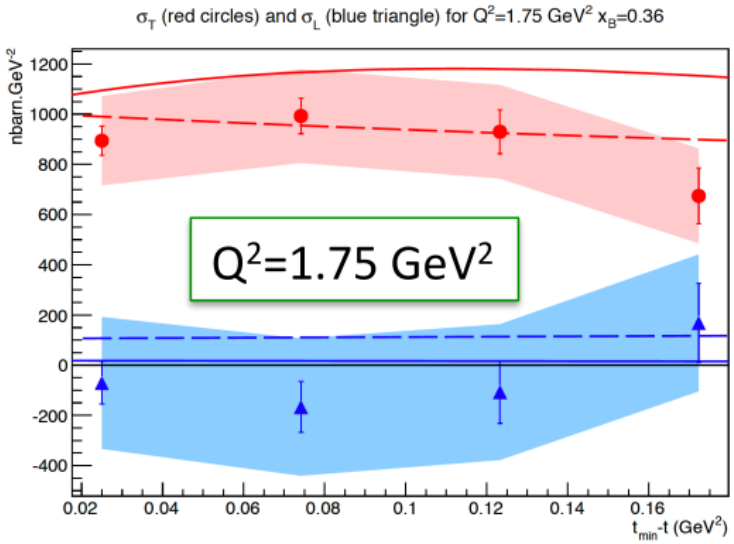


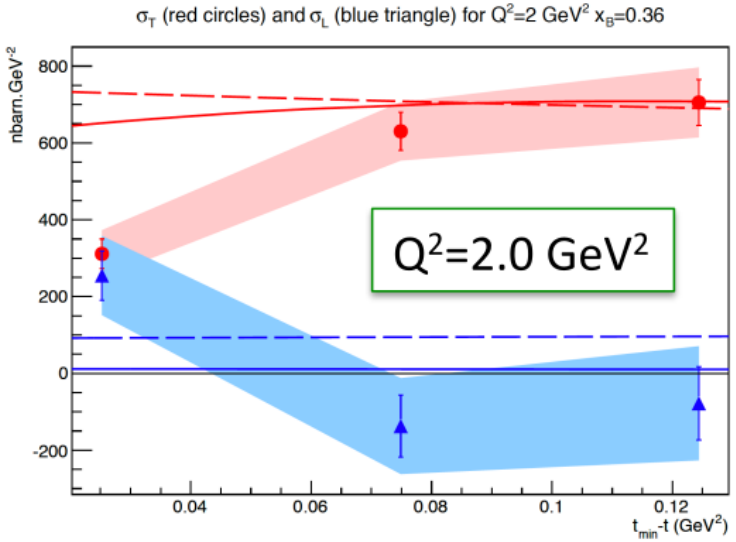
PRL95: 035202 (2017) I.Bedlinsky et al. (CLAS)

solid: P.Kroll & S.Goloskokov
dashed: G.R. Goldstein, J.O. Gonzalez & S.Liuti

Rosenbluth separation of σ_T and σ_L at Hall A



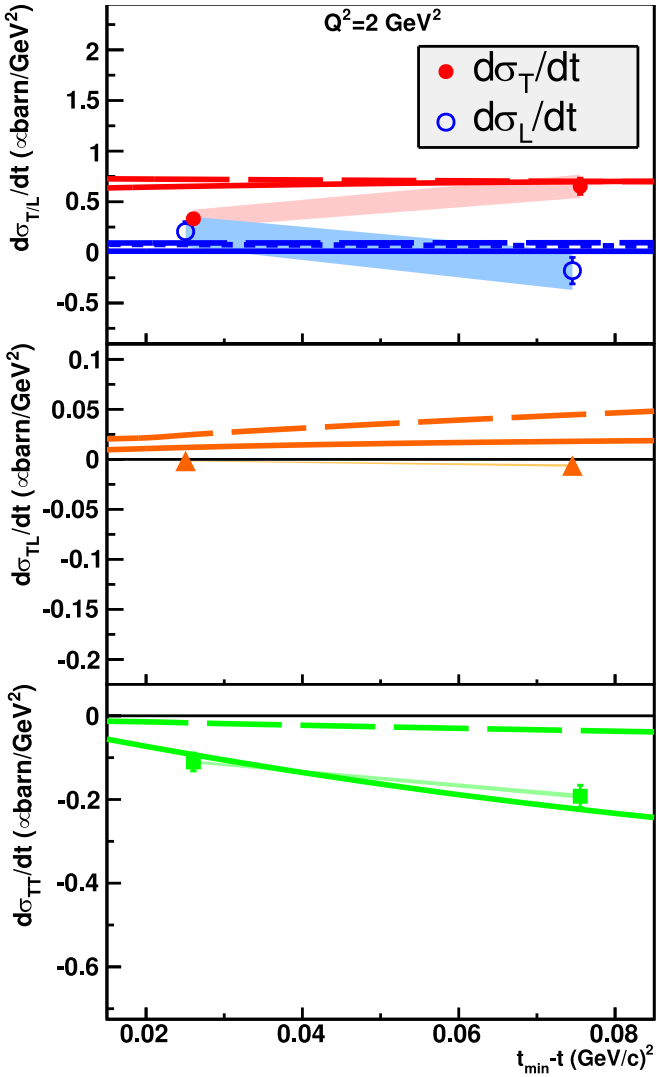




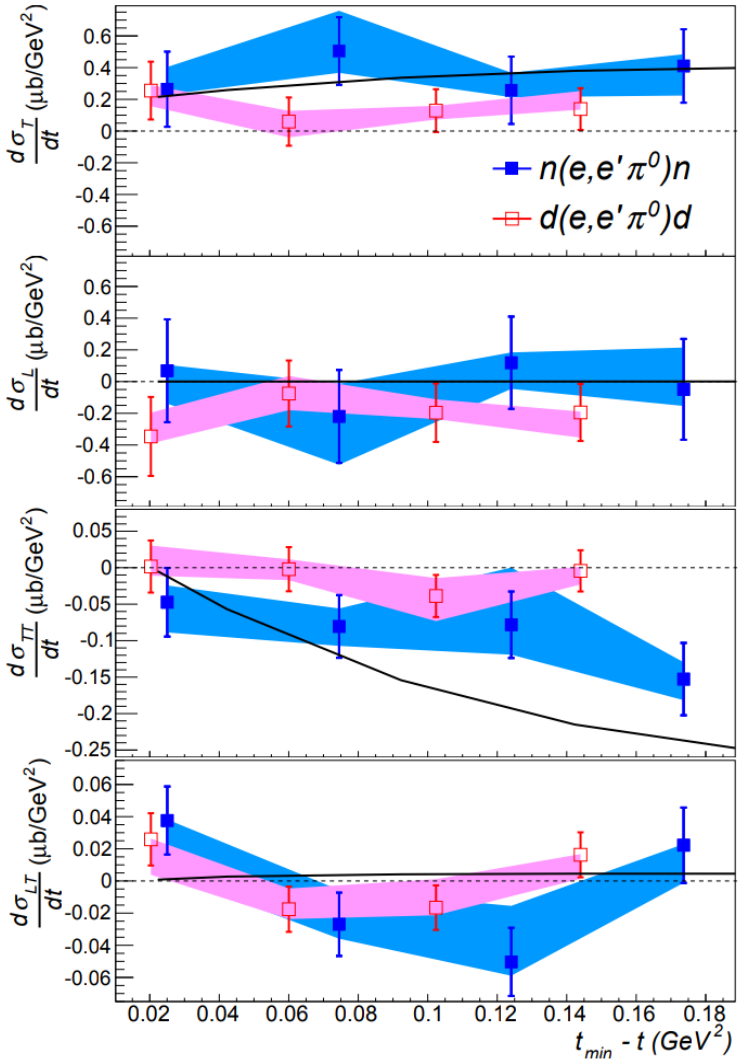
- Experimental **proof** that the transverse π^0 cross section is dominant!
- It opens the direct way to study the transversity GPDs in pseudoscalar exclusive production

Hall A collaboration, PRL 117: 262001 (2016)

π^0 productions on proton and neutron at Hall A



PRL117, 262001 (Hall A)

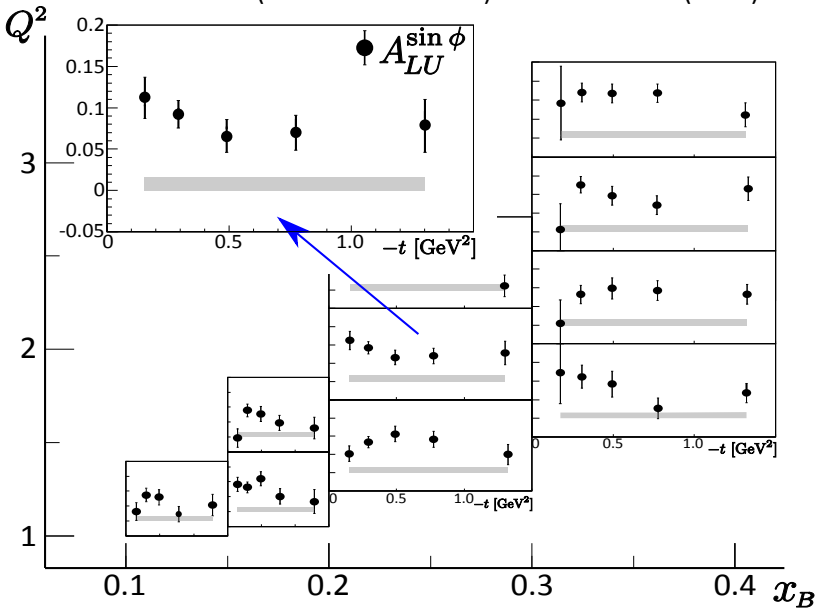


PRL118, 222002 (Hall A)

Spin asymmetry variables

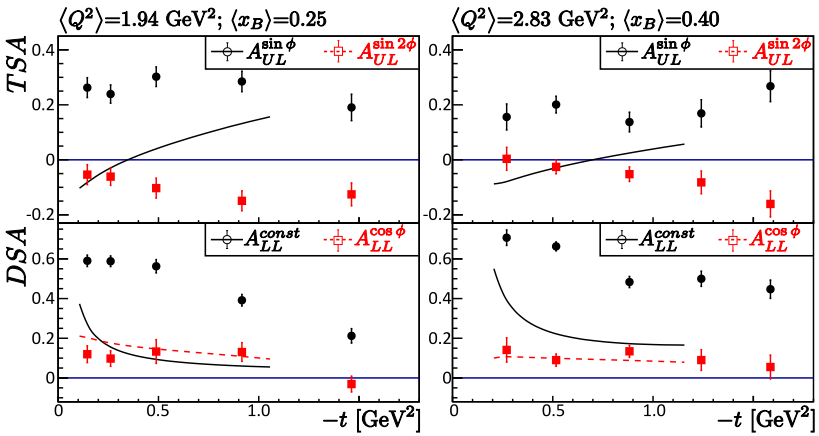
π^0 Beam Spin Asymmetries

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



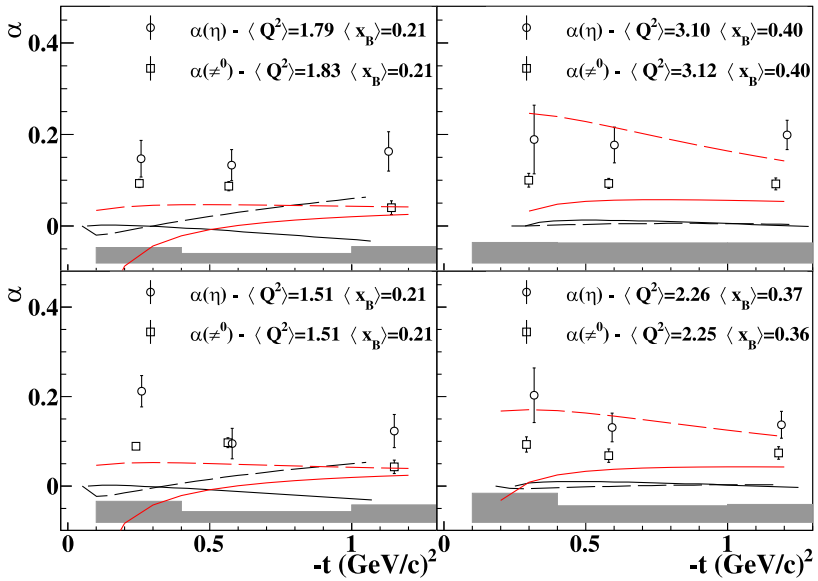
π^0 Target and Double Spin Asymmetries

A. Kim et al. (CLAS) PLB768, 168-173 (2017)



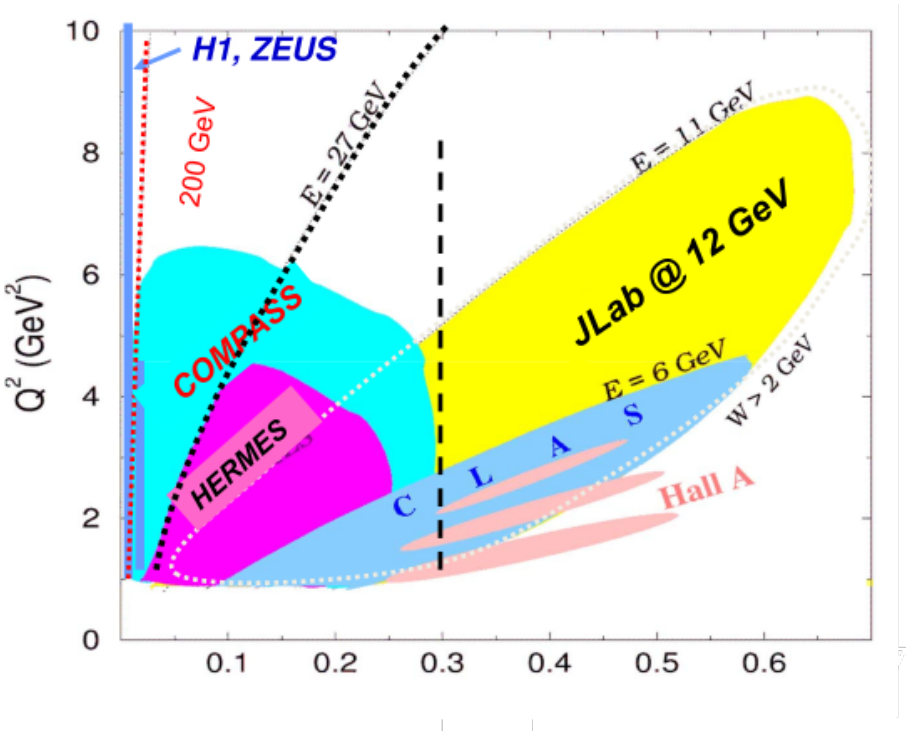
η Beam Spin Asymmetries

B. Zhao, A. Kim et al. (CLAS) submitted to PLB, 2018



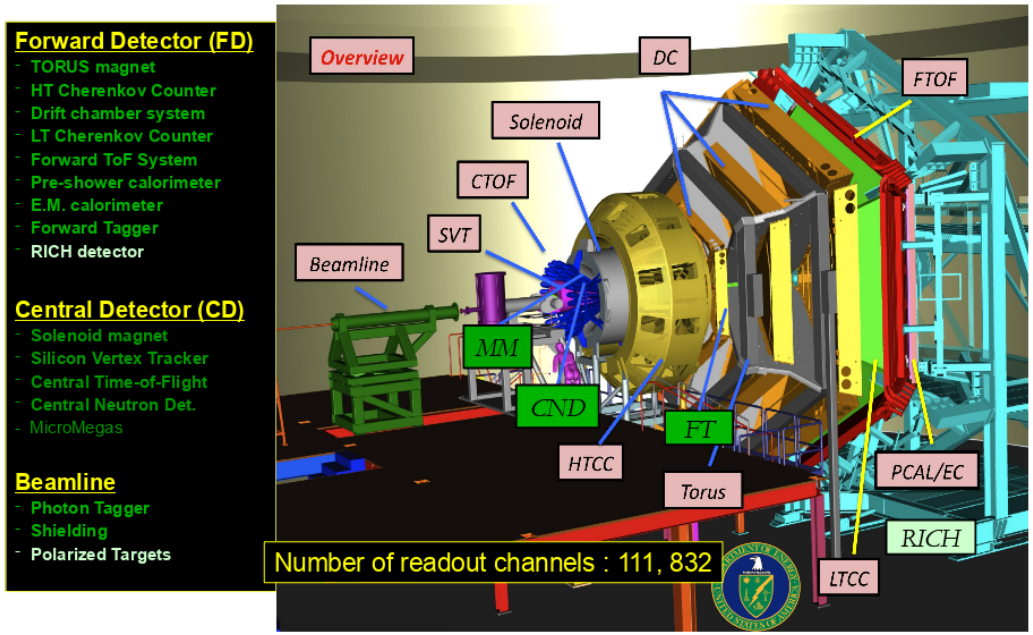
- Large number of single and double spin asymmetries were measured over wide kinematic range
- Asymmetries are harder to interpret since they involve convolutions of chiral even and chiral odd GPDs

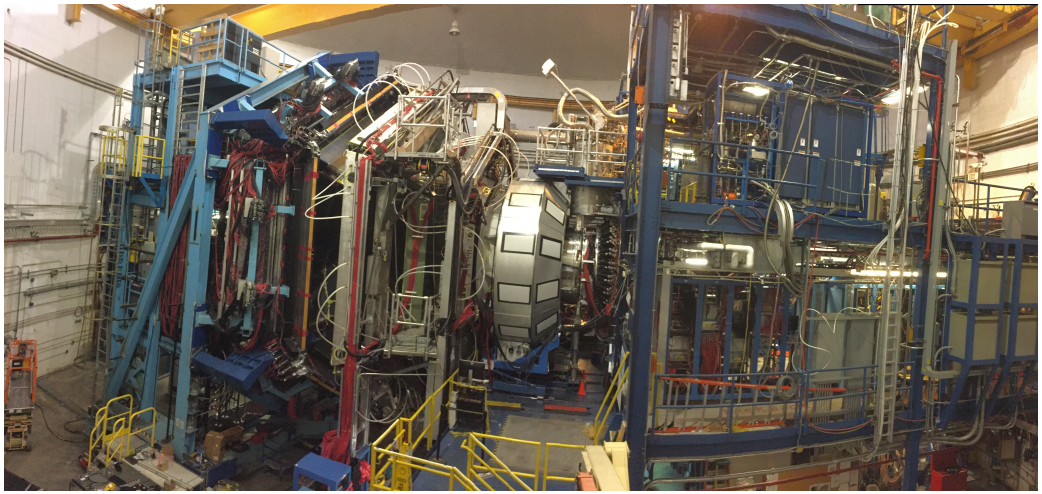
Roadmap: from 6 GeV to 12 GeV



- Early results (2001) from non-dedicated experiment with CLAS (DVCS target spin asymmetry)
- First round of dedicated experiments in Halls A/B at JLab 2004/2005
- Second round of dedicated experiments 2008/2010
- Strong exclusive program at 12 GeV, CLAS12 first experiment data is under analysis

CLAS12 First Experiment

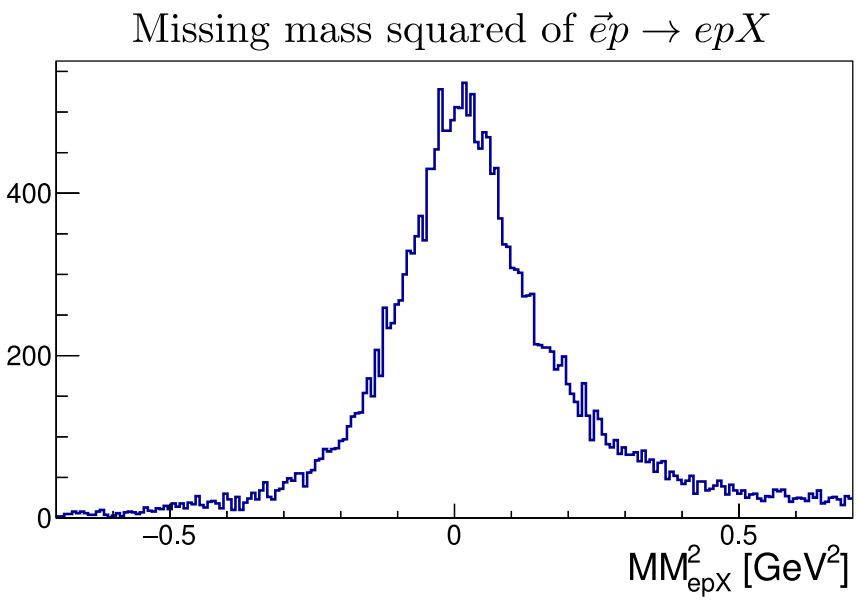


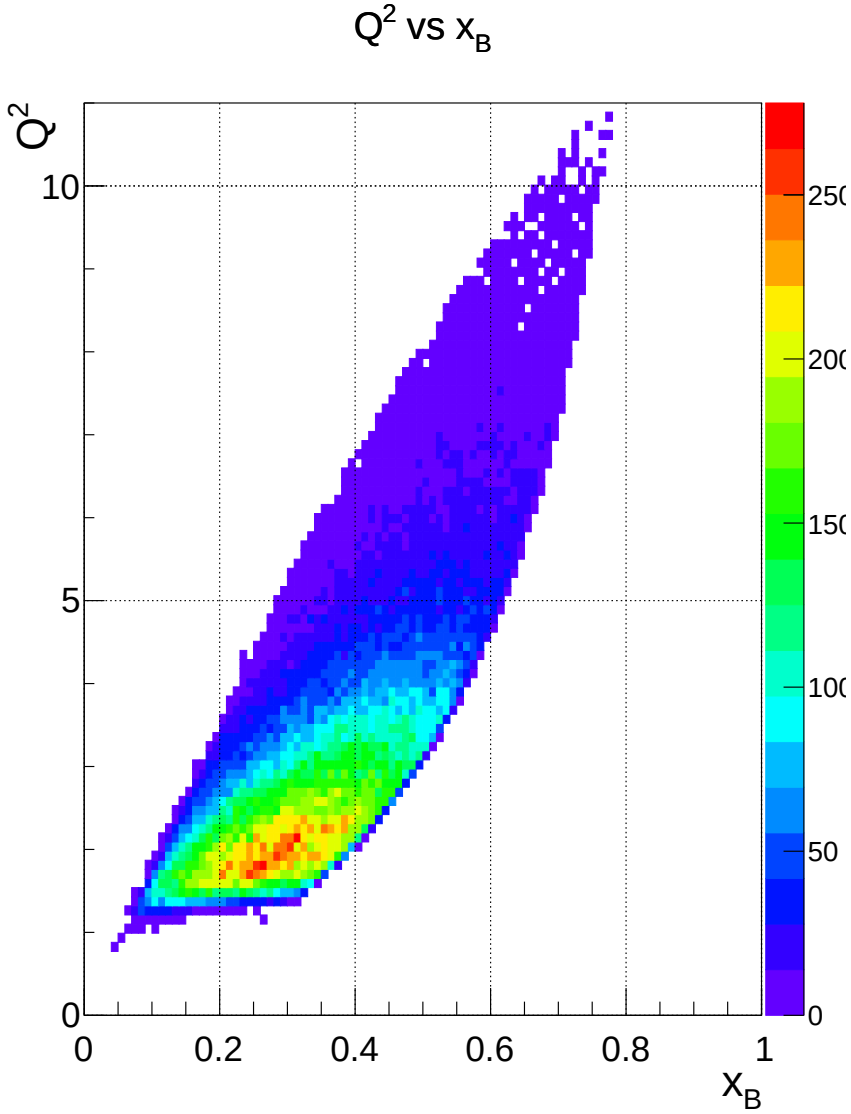


- CEBAF Large Acceptance Spectrometer
- 10.6 GeV longitudinally polarized electron beam
- 85% average polarization
- Liquid hydrogen target
- First CLAS experiment since 12 GeV Upgrade
- The analysis uses 3% of approved beam time

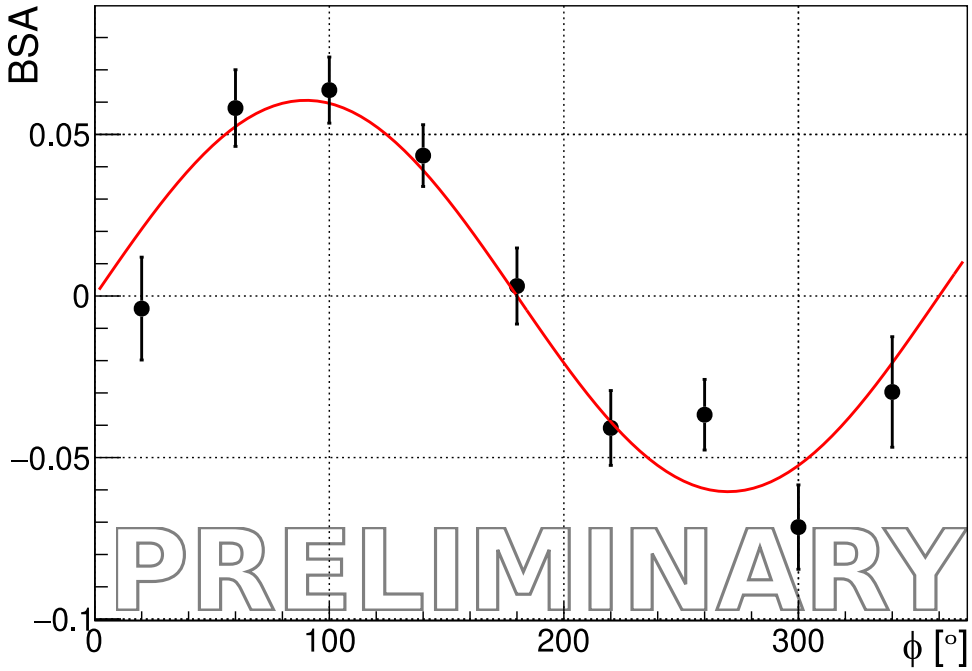
Exclusivity and kinematic coverage

- **DIS region:**
  $W > 2$ GeV, $Q^2 > 1$ GeV^2





Beam spin asymmetry



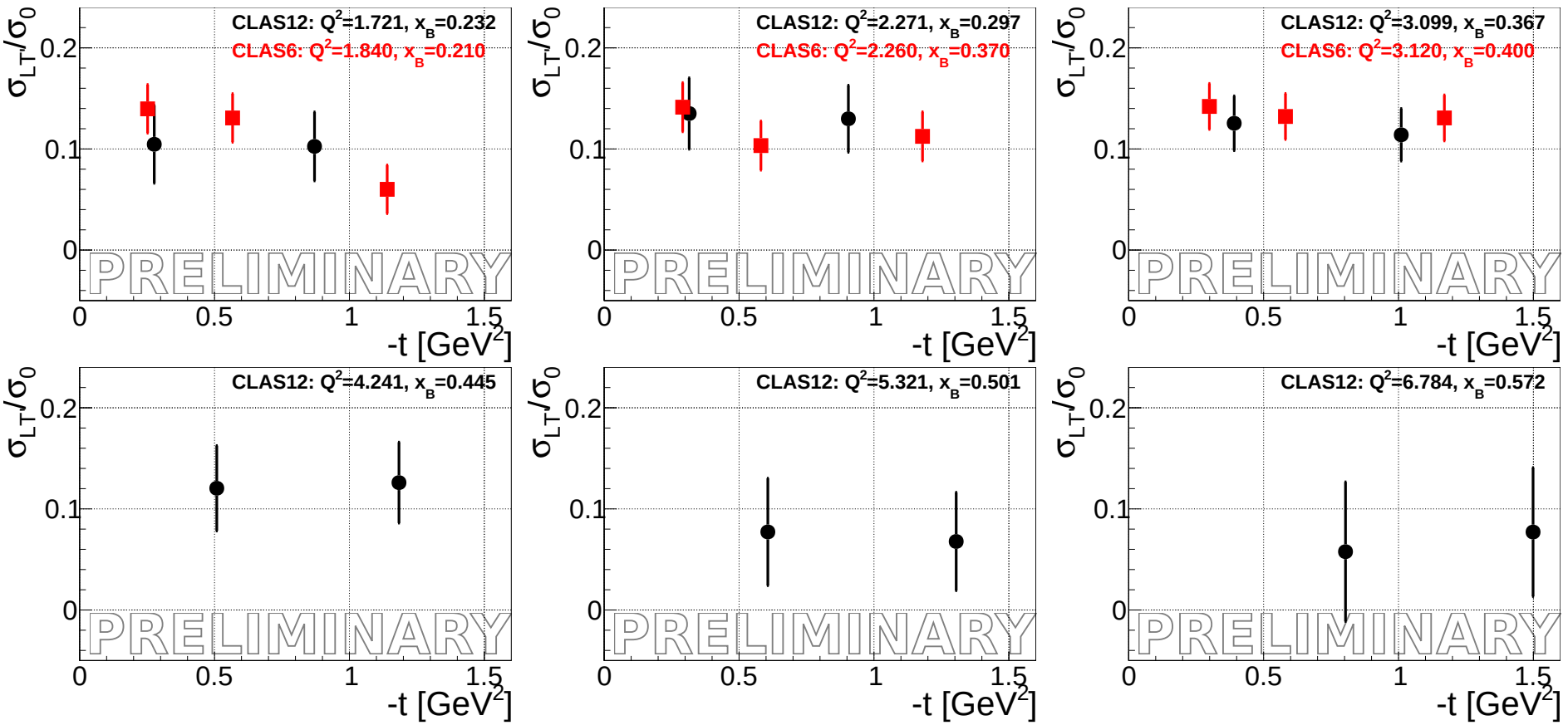
$$BSA = \frac{1}{P_b}\frac{N^+ - N^-}{N^+ + N^-}$$

where $P_b = 85\%$ is an average beam polarization

$$BSA = \sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}$$

- Statistically significant beam spin asymmetry was observed

$\sigma_{LT'}/\sigma_0$ in Q^2,x_B bins



- The preliminary results are compatible with previous measurements

What can we learn about the nucleon structure from chiral-odd GPDs?

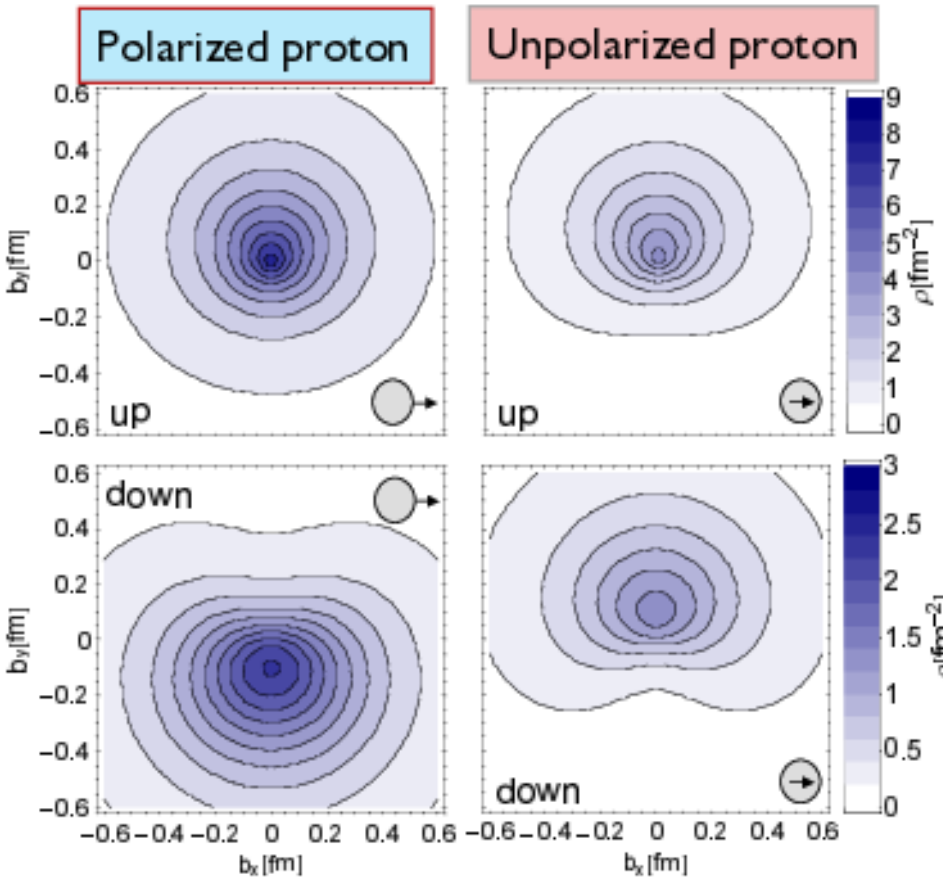
- $\bar{E}_T$ is related to the distortion of the polarized quark distribution in the transverse plane for an unpolarized nucleon
- H_T is related to transversity PDF h_1^q and tensor charge

Transverse densities for u and d quarks in the proton

u quarks

Strong distortions for unpolarized quarks in transversely polarized proton

d quarks



Strong distortions for transversely polarized quarks in an unpolarized proton

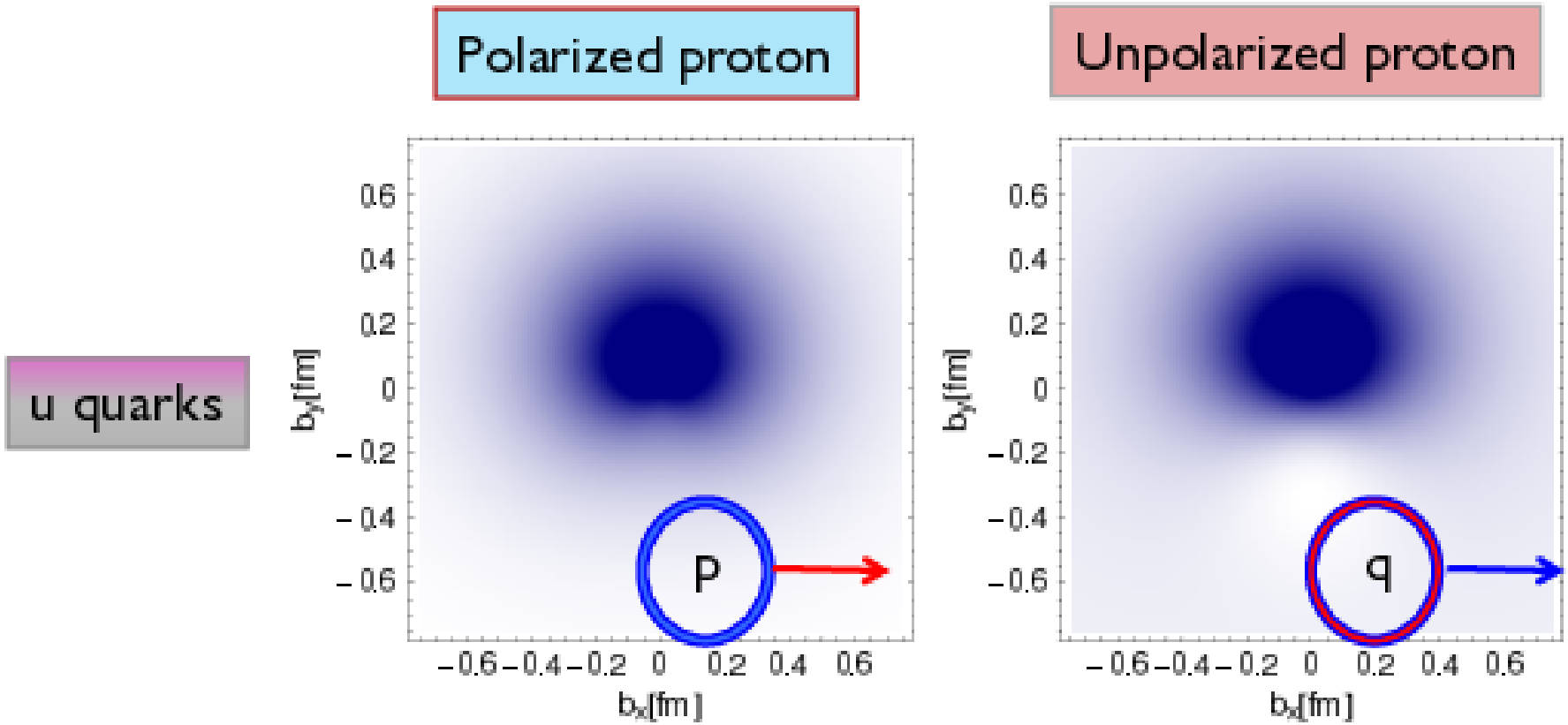
Lattice calculations

Controlled by E

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

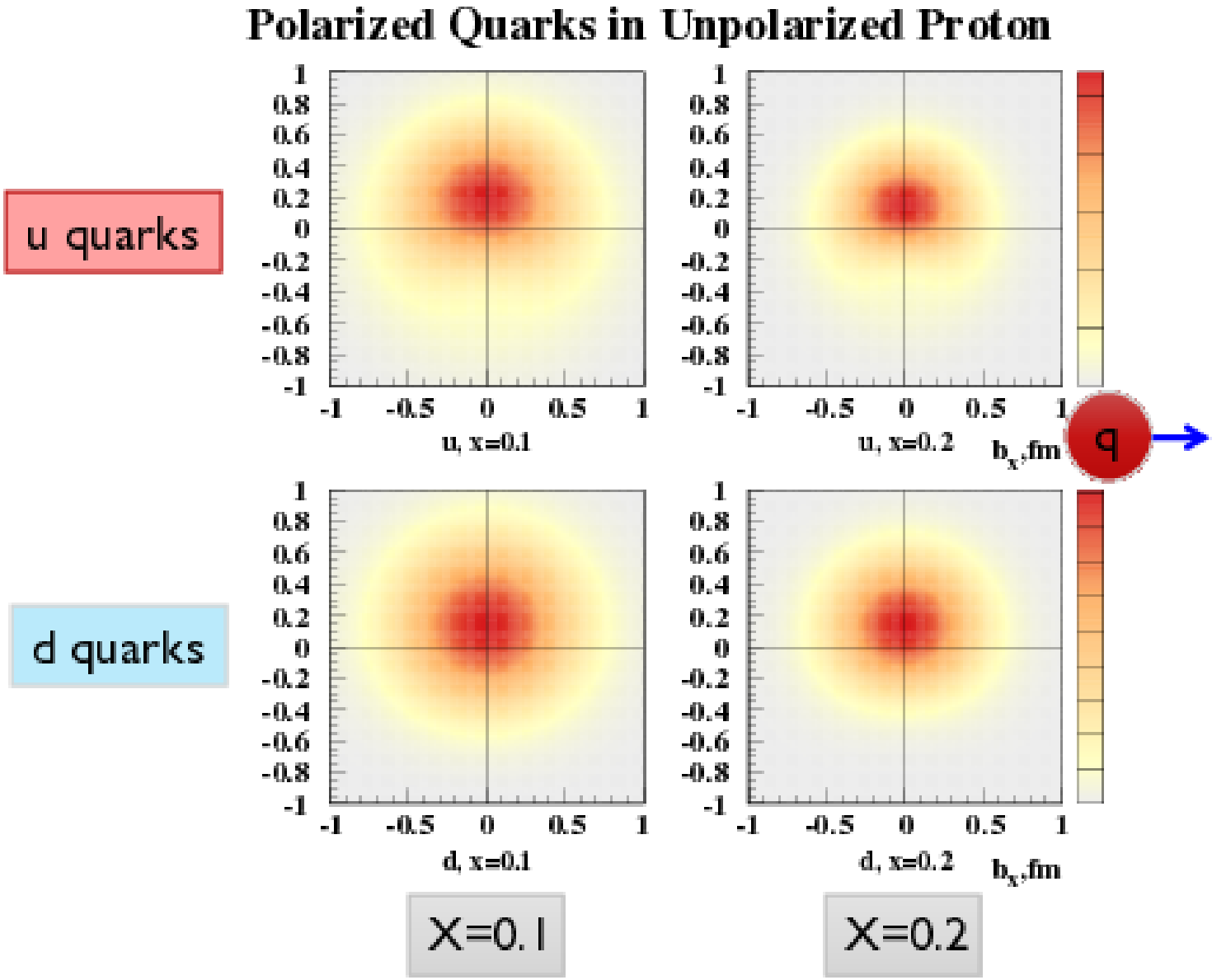
PRL98, 222001, Gockeler (2007)

Transverse densities for u and d quarks in the proton



M. Diehl, Ph. Hagler Eur.Phys.J.C44:87-101,2005

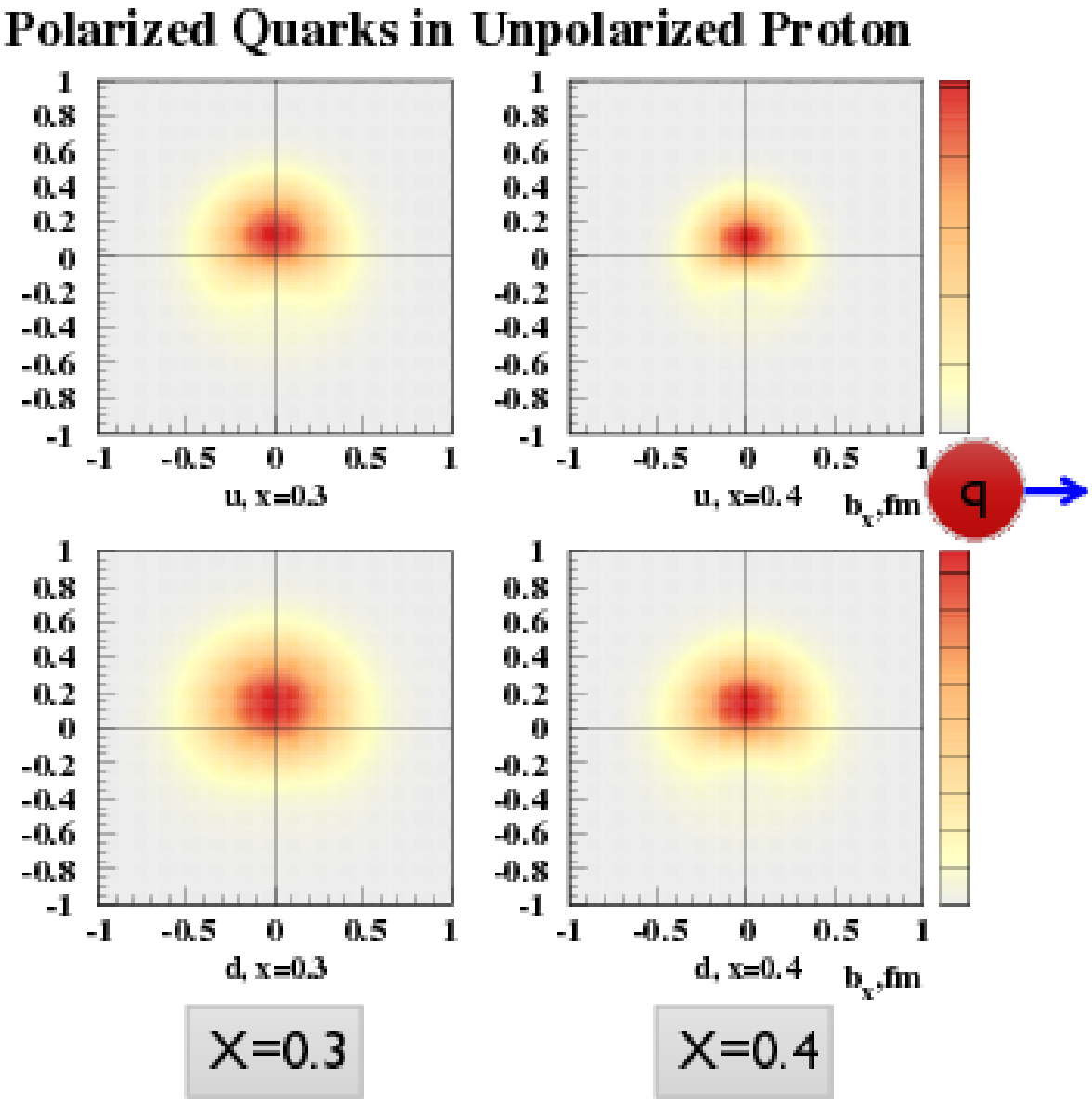
Transverse densities for u and d quarks in the proton



Transverse densities for u and d quarks in the proton

u quarks

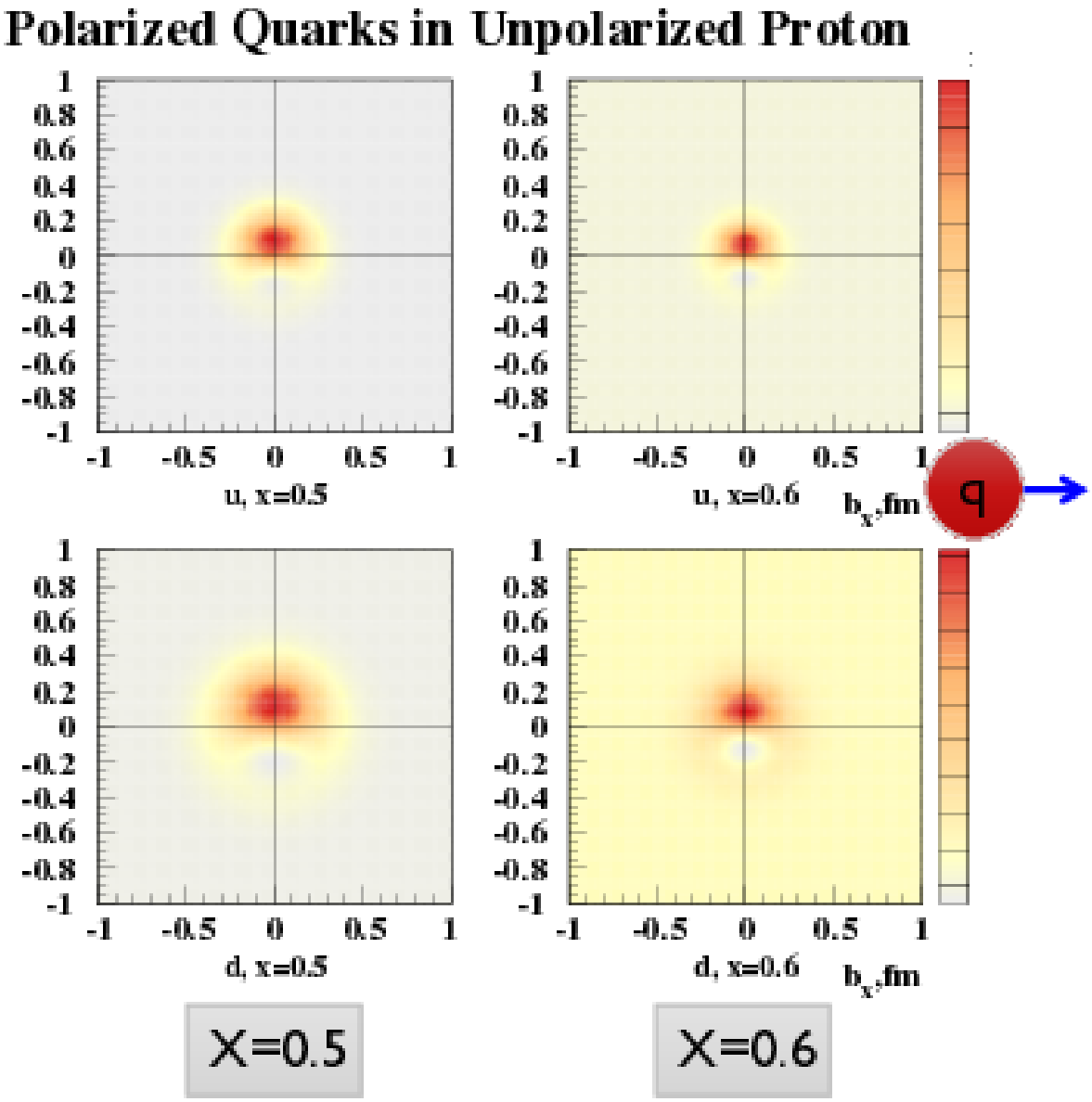
d quarks



Transverse densities for u and d quarks in the proton

u quarks

d quarks



Summary

- The 6 and 12 GeV experimental data provide rich constraints for chiral-odd GPDs models and parameterizations and access the distributions of polarized quarks in the nucleon
- The combined π^0 and η electroproduction on proton from CLAS, as well as data on proton and neutron from Hall A, allow the insight into the flavor decomposition of transversity GPDs
- CLAS12 preliminary results indicate a promising future for Deeply Virtual π^0 Electroproduction measurements
- 10.6 GeV electron beam extend our reach to the higher kinematic regions