Studies of Transversity GPDs

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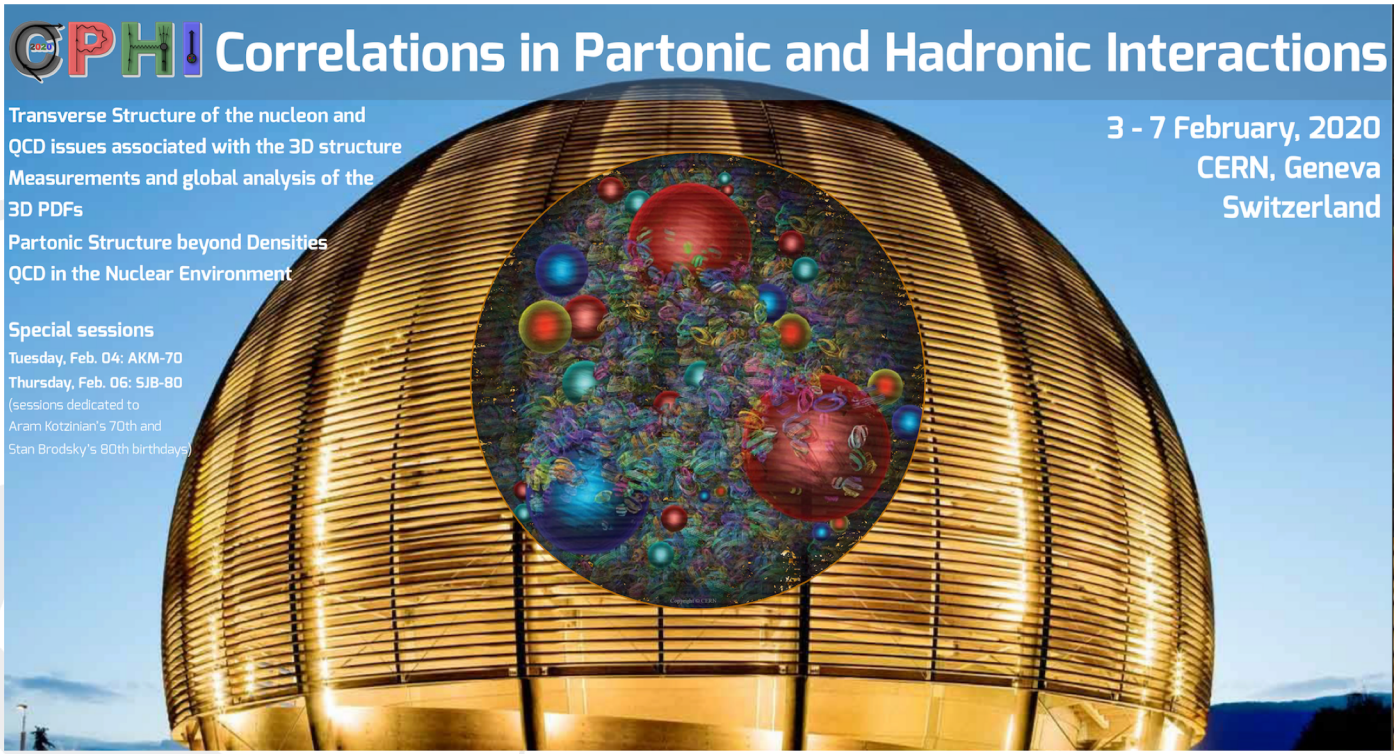
Jefferson Lab



CPHI 20220

February 5th, 2020

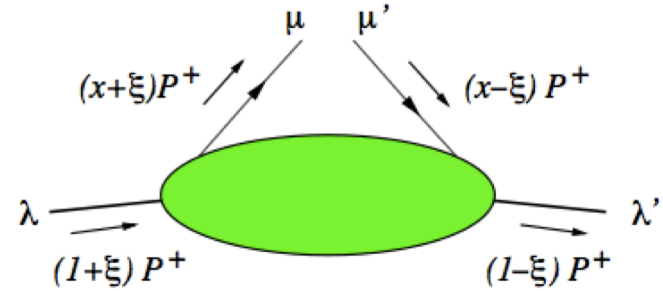
U.S. DEPARTMENT OF ENERGY

Office of Science

Outlook

- What we know about transversity GPDs
- Transversity GPDs in pseudoscalar meson electroproduction
- Review of the experimental data
- GK Transversity GPD model
- Extraction of the transversity GPDs parameters from Global Fit
- CLAS12, status of data taking and data 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

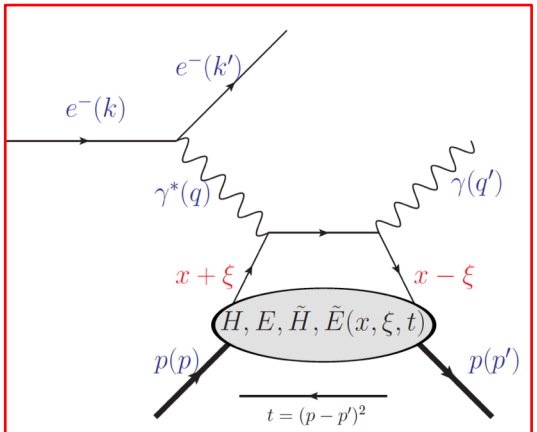
$$H_T^q, \tilde{H}_T^q, E_T^q, \bar{E}_T^q = 2\tilde{H}_T^q + E_T^q$$

DVCS

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

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

- DVCS accesses <u>only chiral-even</u> GPDs due to suppression of the helicity flip amplitude



DVCS at leading order

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

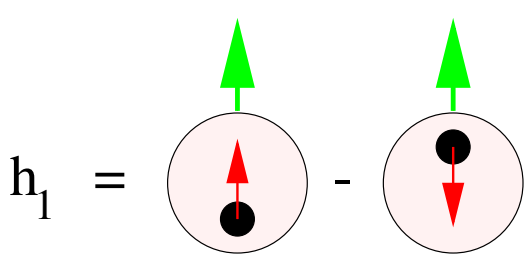
$$t = (p - p')^2$$

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

Transversity GPDs

- Proton anomalous tensor magnetic moment

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

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

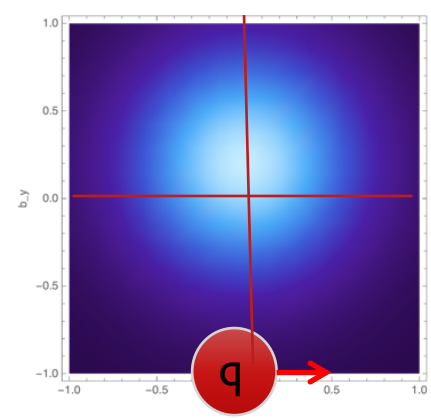
- Proton tensor charge

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

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

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

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

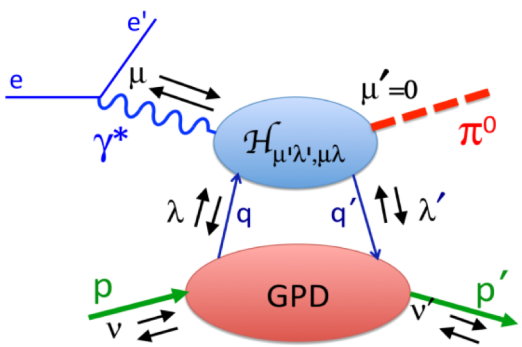


$$ep \to ep\pi^0$$

DVMP Leading Twist

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

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



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

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

$$Q^2 \to \infty$$

x_B, t *fixed*

Forward limit

$$\tilde{H}^q(x,0,0) = \Delta q(x)$$

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

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

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

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

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

Leading Twist Failed to describe data the cross section

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

Leading twist σ_L – dominance,

- Cross section was off by an order of magnitude
- 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

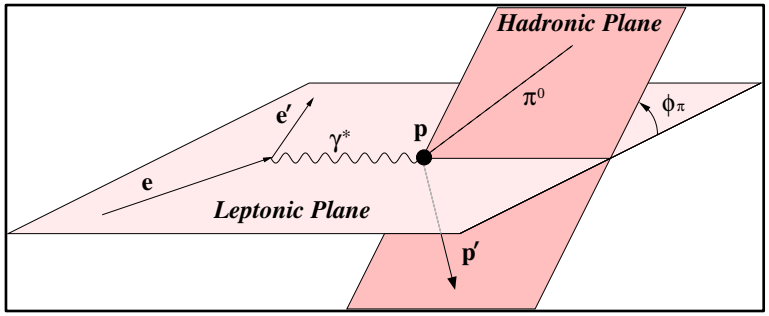
$$\langle\tilde{H}\rangle = \sum_\lambda \int_{-1}^{1} dx M(x,\xi,Q^2,\lambda)\tilde{H}(x,\xi,t)$$

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

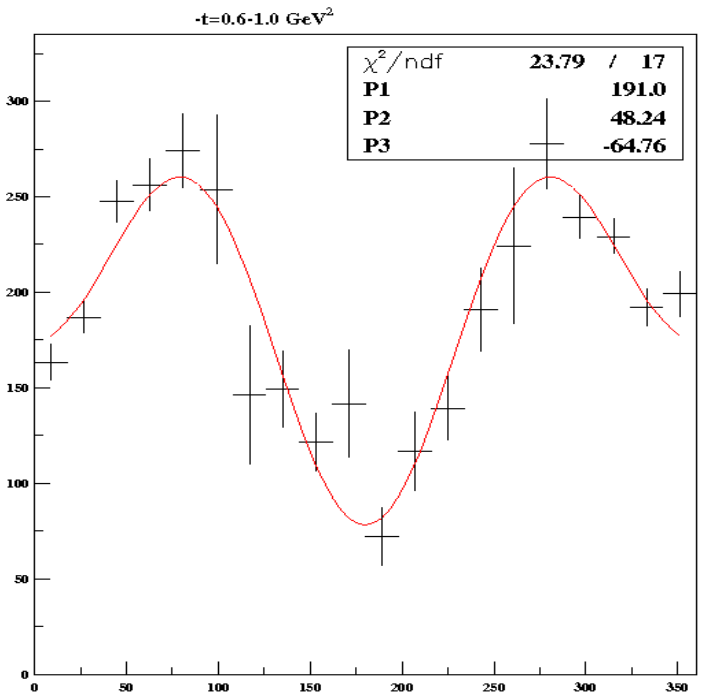
The brackets <F> denote the convolution of the elementary process with the GPD F (generalized form factors)

Structure Functions

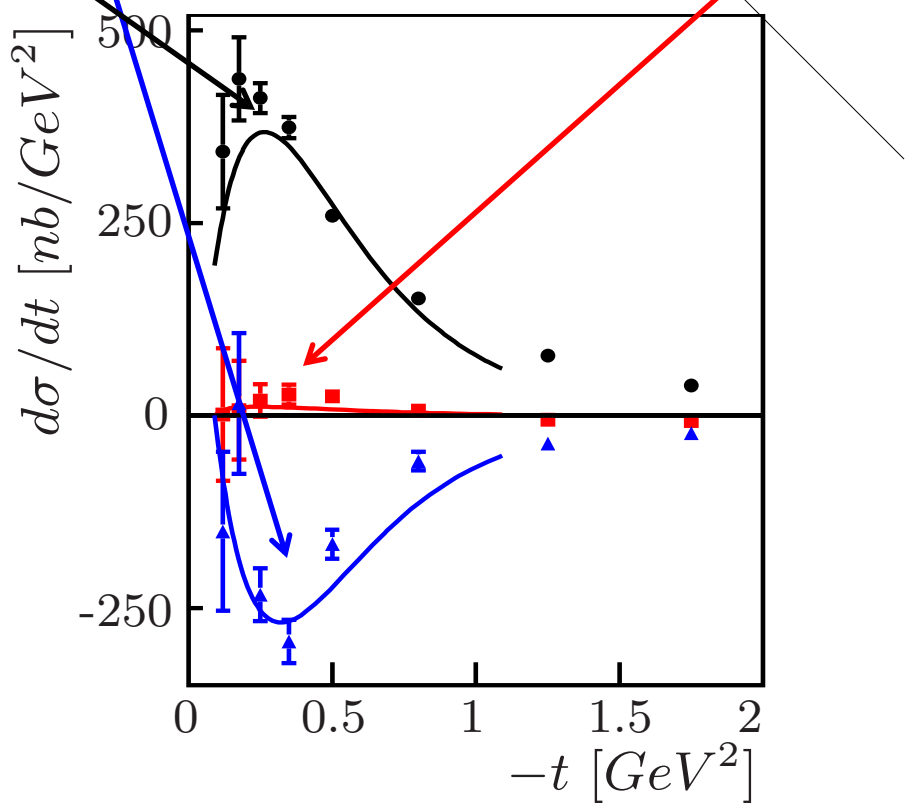
$\sigma_U = \sigma_T + \varepsilon\sigma_L \quad \sigma_{TT} \quad \sigma_{LT}$



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



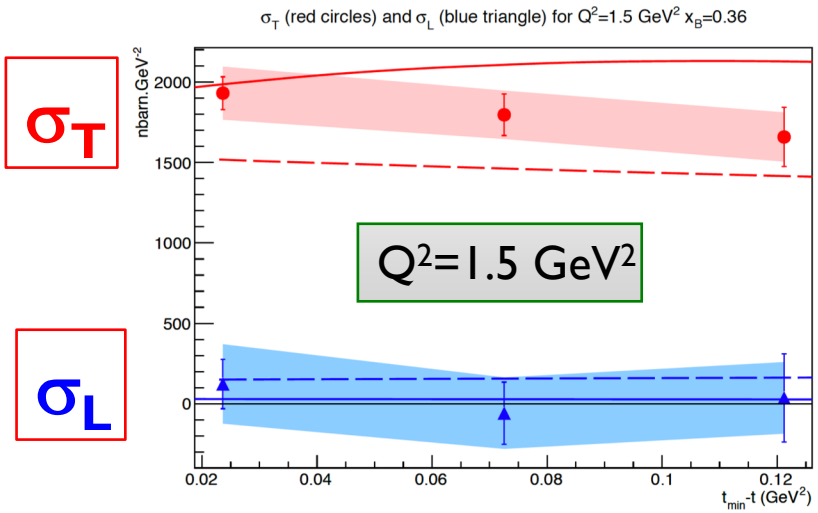
ϕ distribution

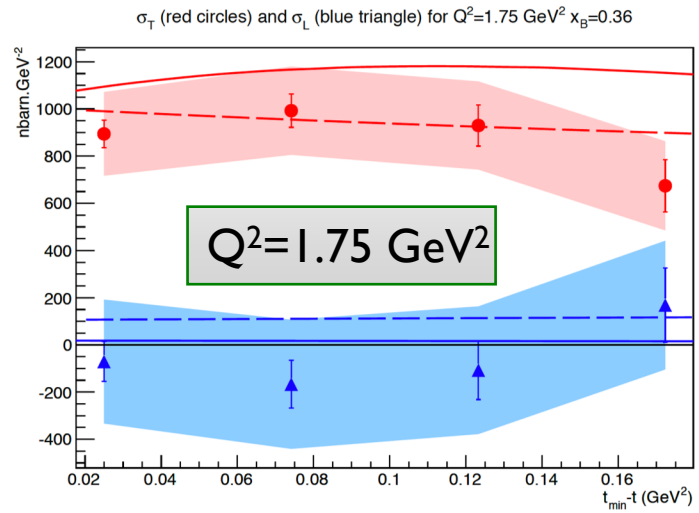


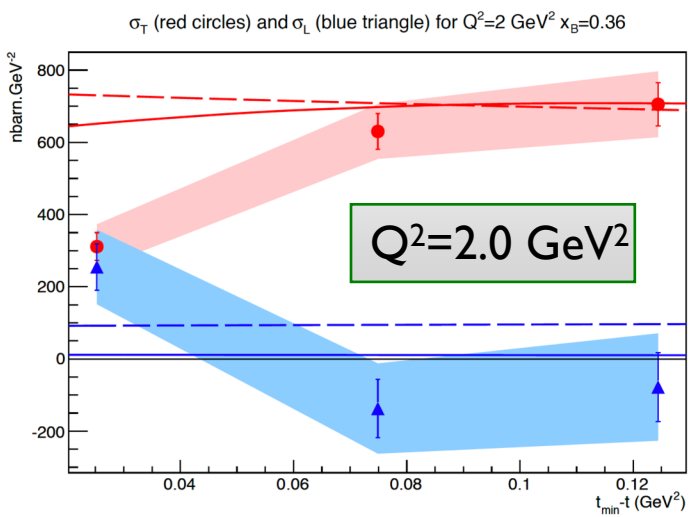
-t

Rosenbluth separation σ_T and σ_L Hall-A Jefferson Lab

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

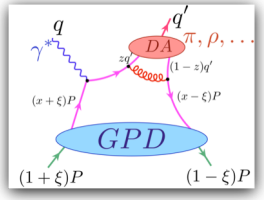






- Experimental **proof** that the transverse π^0 cross section is dominant!
- It opens the direct way to study the transversity GPDs in pseudoscalar exclusive production

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



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

Structure functions and GPDs

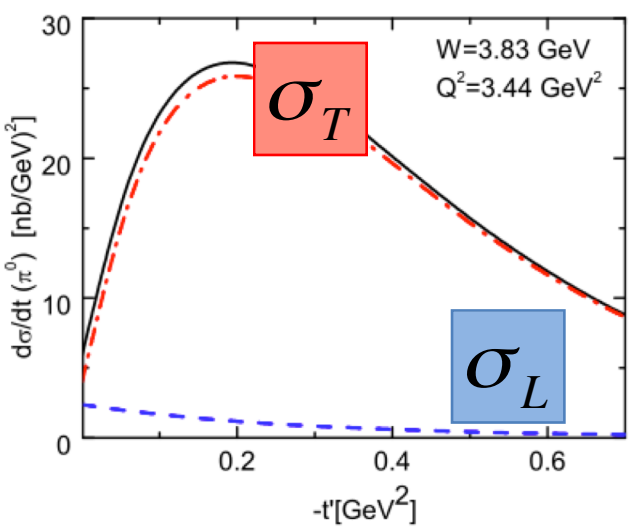
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}(\sigma_T + \epsilon\sigma_L + \epsilon\cos 2\phi_\pi \sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \sigma_{LT})$$

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

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

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

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



Transversity GPD model

S. Goloskokov and P. Kroll

S. Liuti and G. Goldstein

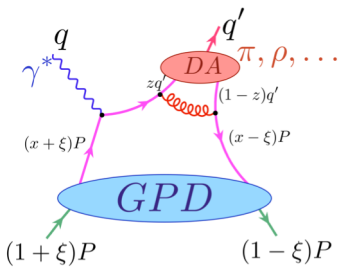
- $\sigma_L \ll \sigma_T$

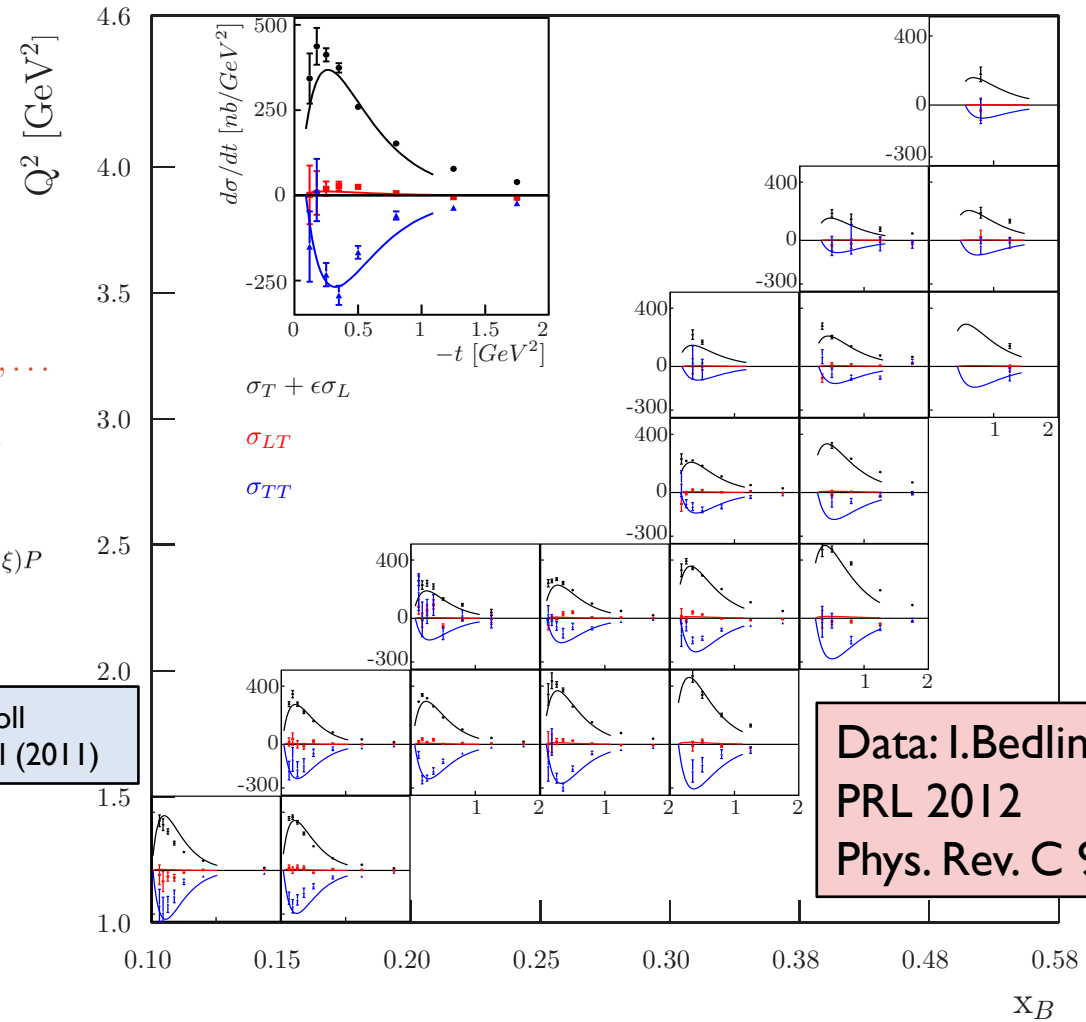
The brackets <F> denote the convolution of the elementary process with the GPD F (Generalized Form Factors, GFF)

CLAS: π^0 Structure Functions

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

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





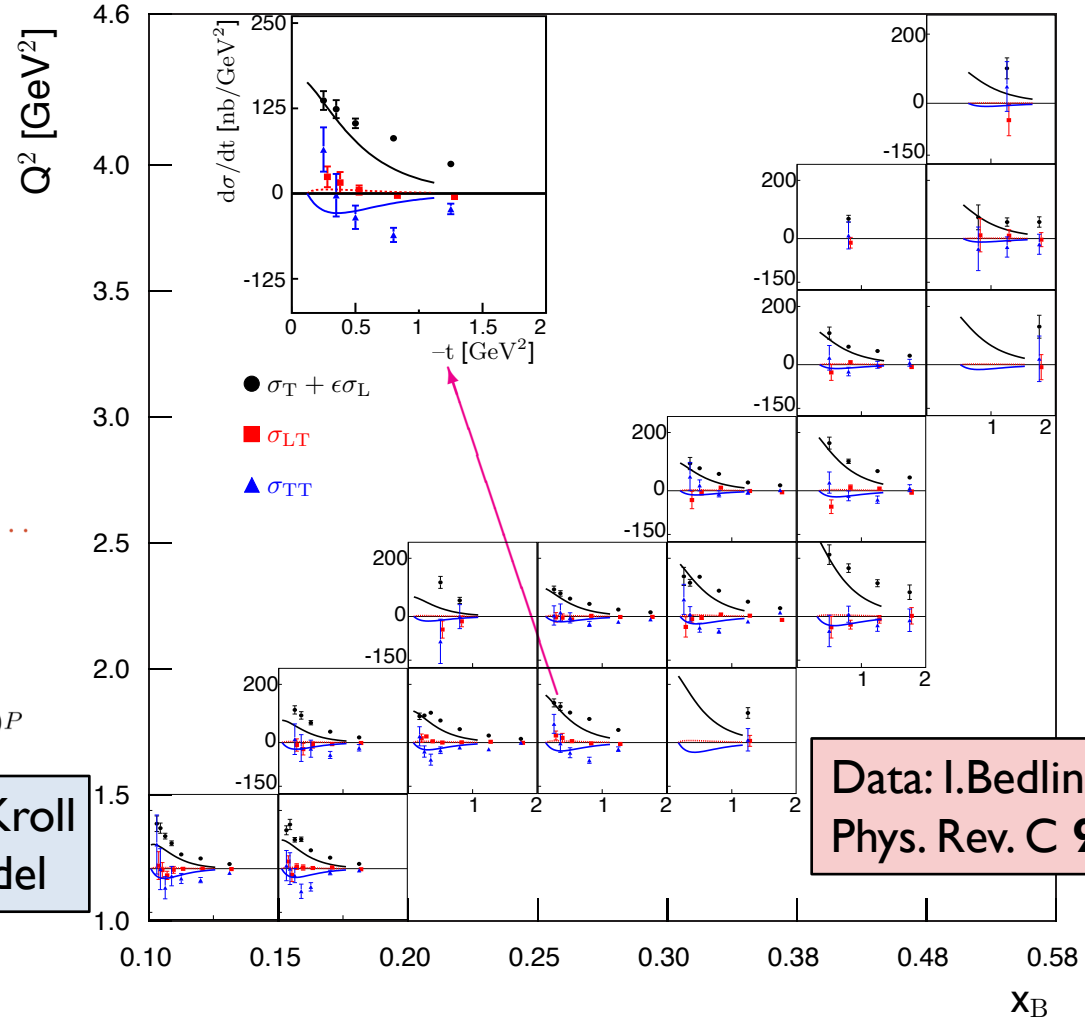
Curves: Goloskokov, Kroll
Transversity GPD model (2011)

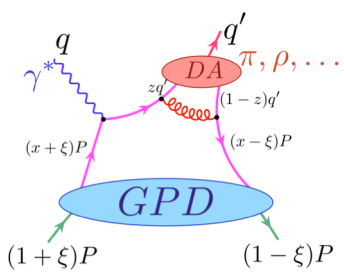
Data: I.Bedlinskiy et al. (CLAS)
PRL 2012
Phys. Rev. C 90, 039901 (2014)

CLAS: η Structure Functions

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

$$\gamma^* p \to p\eta$$





Curves: Goloskokov, Kroll
Transversity GPD model

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

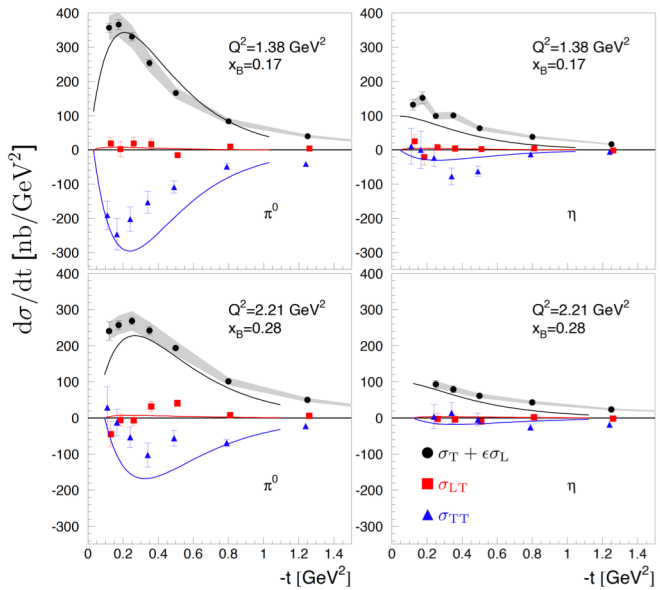
CLAS6 π^0/η Comparison

π^0 η

σ_u

σ_{LT}

σ_{TT}

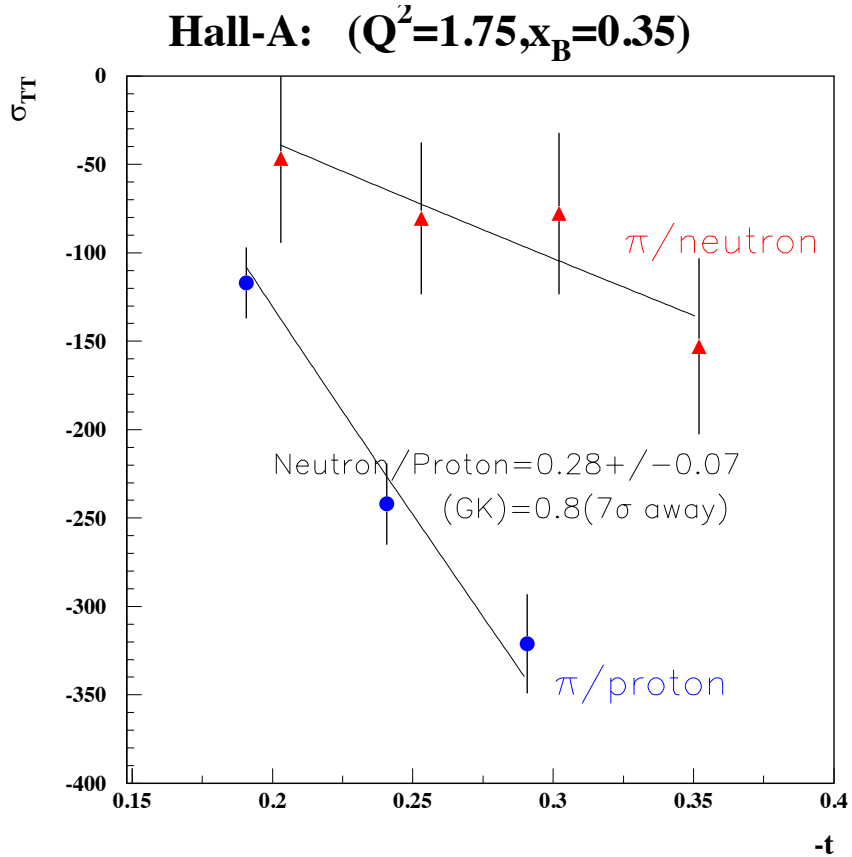


CLAS-Phys.Rev.C95(2017)

- 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

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



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

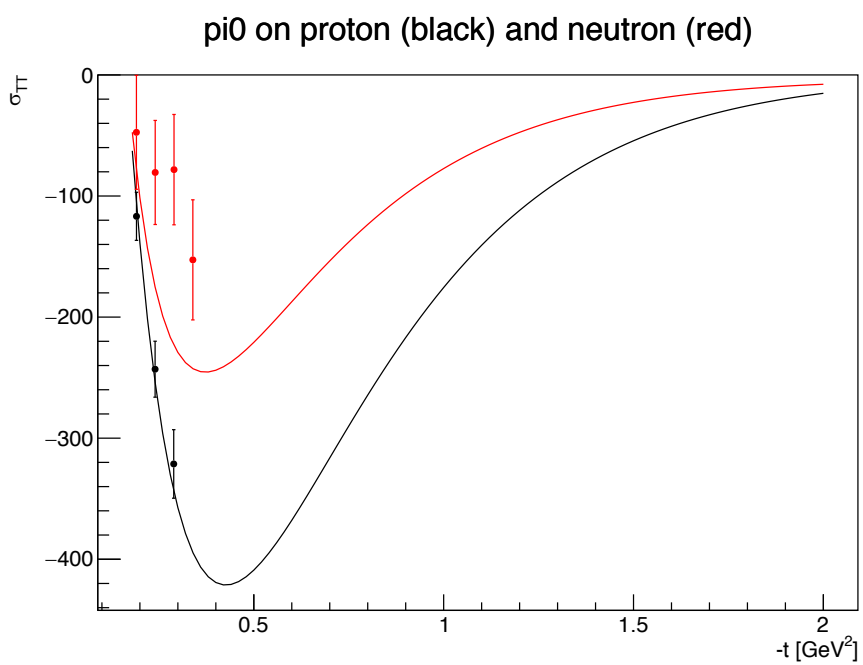
$$\bar{E}_T^{\pi/proton} = \frac{1}{3\sqrt{2}}(2\bar{E}_T^u + \bar{E}_T^d) \quad (1)$$

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

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

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

GK model of σ_{TT}



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

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

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

$$\mu p \to \mu p \pi^0$$

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
- **<Q2>=2.0 GeV^2**
- **<xB>=0.093**
- <-t>=0.256 GeV^2

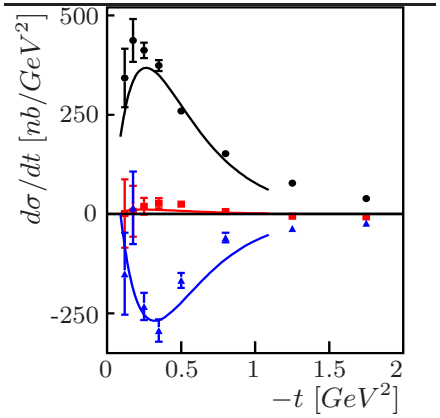
- 0.08 GeV^2 < ltl < 0.64 GeV^2
- 1 GeV^2 < Q2 < 5 GeV^2
- 8.5 GeV < ν < 28 GeV

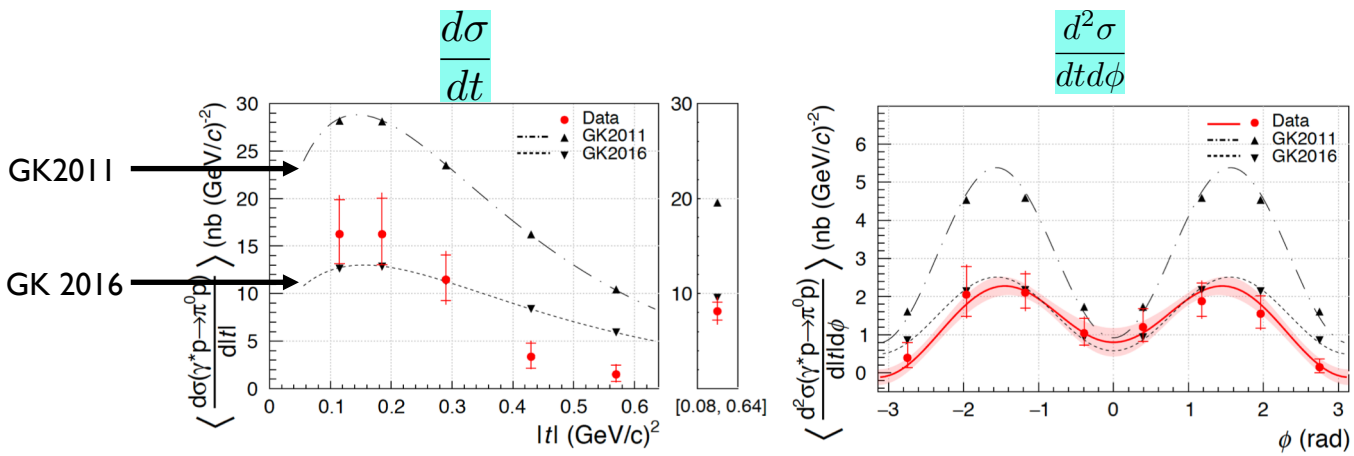
COMPASS-Jlab comparison

CLAS 2000 points

COMPASS data
(5 points)

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





- Factor of two difference between GK2011 and GK2016

Generalized Form Factors

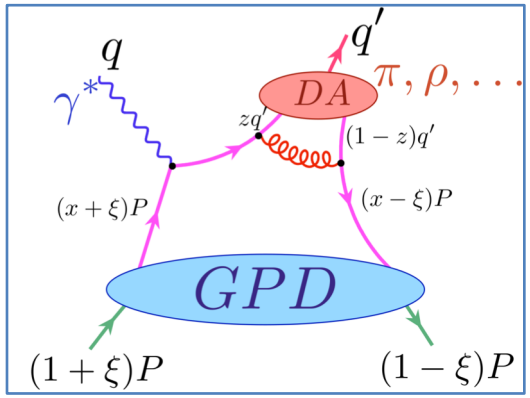
$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_P^2}{Q^8}\left[(1-\xi^2)\,|\langle H_T\rangle|^2 - \frac{t'}{8m^2}|\langle \bar{E}_T\rangle|^2\right]$$

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

Goloskokov, Kroll
Transversity GPD model

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

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



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

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

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

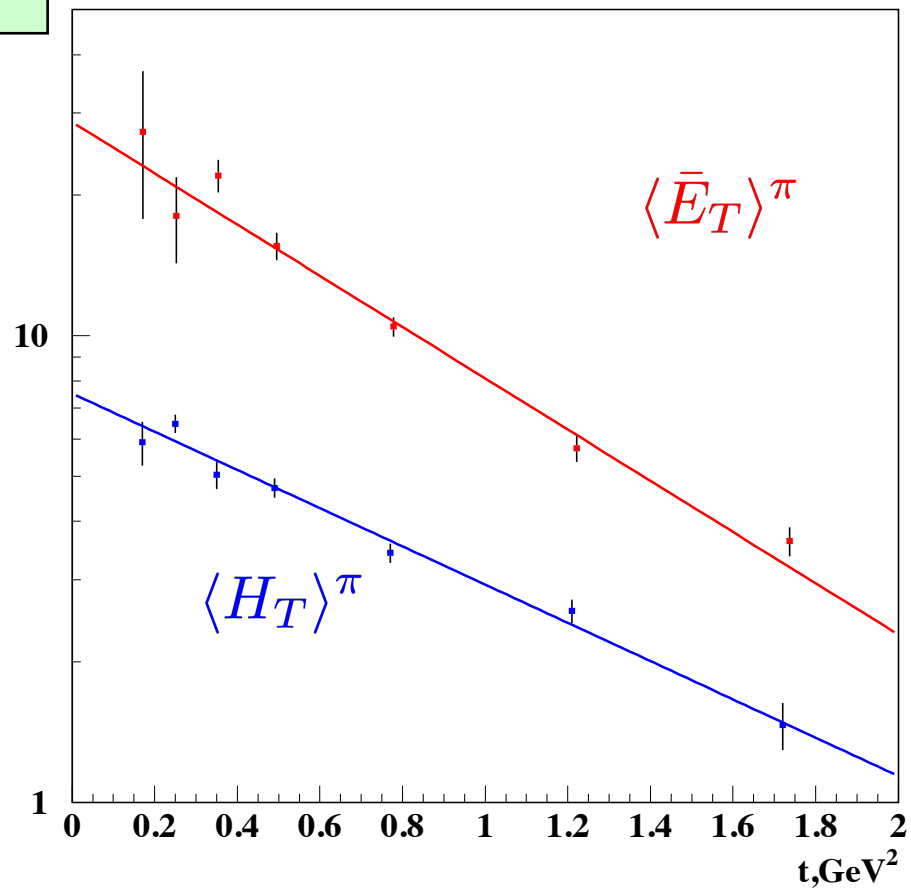
$\bar{E}_T = 2\tilde{H}_T + E_T$

- *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.

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

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

VK, arXiv:1601.04367

Goloskokov-Kroll Model

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

ξ=0 Limit

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

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

$$\xi \to 0$$

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

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

ξ=0 Limit

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

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

$$\xi \to 0$$

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

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

We end up with 4 parameters for u-quarks
and 4 parameters for d-quarks

Flavor Decomposition

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

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

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

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

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

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

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

The contribution from sea quarks is cancelled out.

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

status report

<u>Data</u>

- CLAS π^0/η out of proton
- Hall-A π^0 out of proton and neutron
- COMPASS π^0
- $\bar{E}_T(x,t,\xi)$ parameters only
- Fit σ_{TT}

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

Fit Parameters

	GK model	Fit	+/-
N^u	4.82	22	3.7
b^u	0.5	1.08	0.32
$\alpha_0{}^u$	0.3	-0.15	0.06
α'^u	**0.45**	0.23	0.1
N^d	3.57	9.3	6.6
b^d	0.5	0	1.5
$\alpha_0{}^d$	0.30	0.16	0.17
α'^d	**0.45**	1.44	0.48

very preliminary

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

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

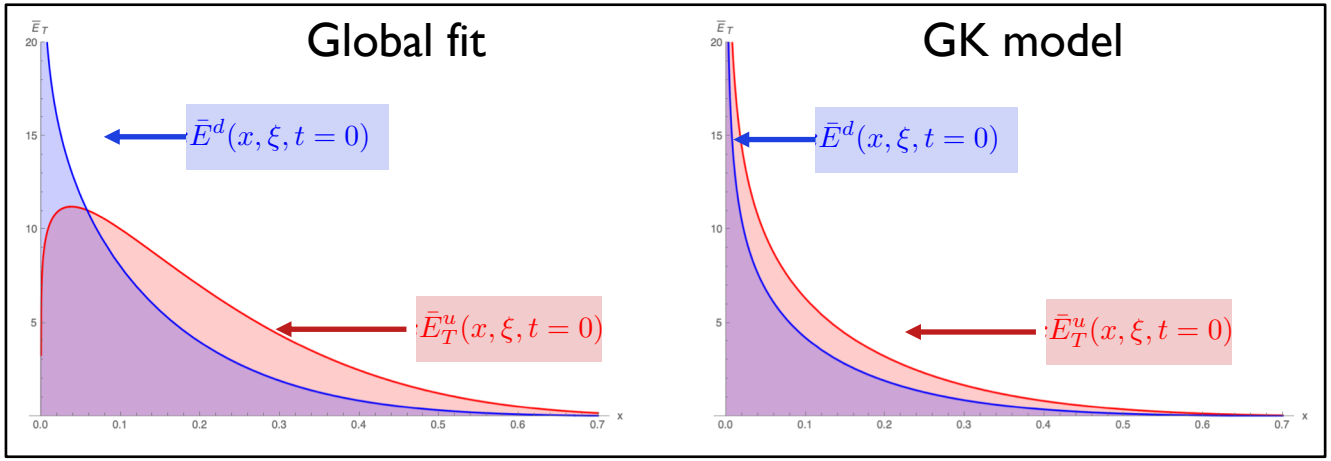
Estimate of Proton Anomalous Tensor Magnetic Moment

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

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

	GK model Lattice	Global Fit	Chiral Soliton model
κ_T^u	2.07	3.1	3.56
κ_T^d	1.35	2.4	1.83

Global fit statistical and systematic errors analysis is in progress



Note the same sign for $\bar{E}_T^u(x,\xi,t=0)$ and $\bar{E}^d(x,\xi,t=0)$

Estimate of Proton Tensor Charge

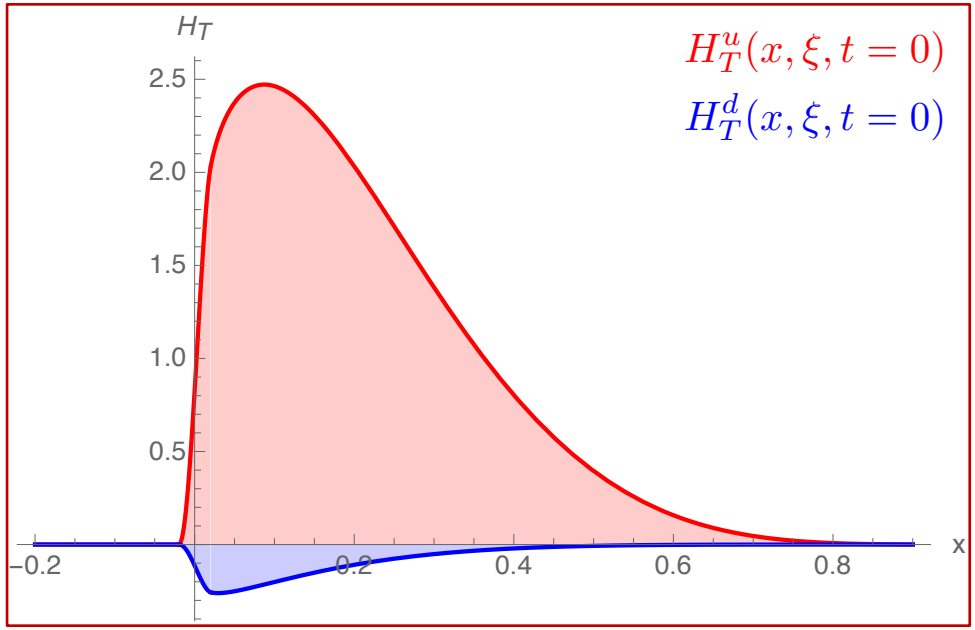
(still GK model, results from the global fit are coming)

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

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

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

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

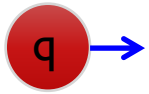


Theory average $\overline{\delta_T u} = 0.803(17)\,,\ \overline{\delta_T d} = -0.216(4)$

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

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

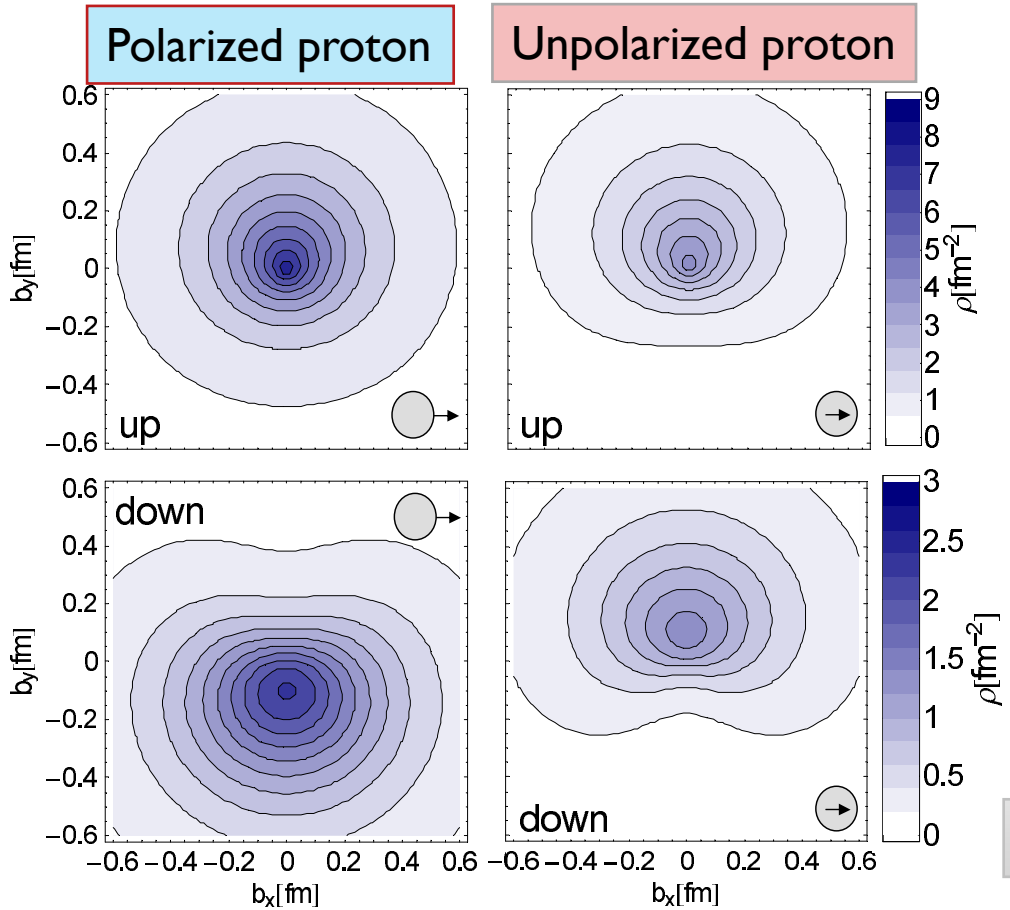


Integrated over *x* Transverse Densities for u and d Quarks in the Proton

u quarks

Strong distortions for unpolarized quarks in transversely polarized proton

d quarks



Strong distortions for transversely polarized quarks in an unpolarized proton

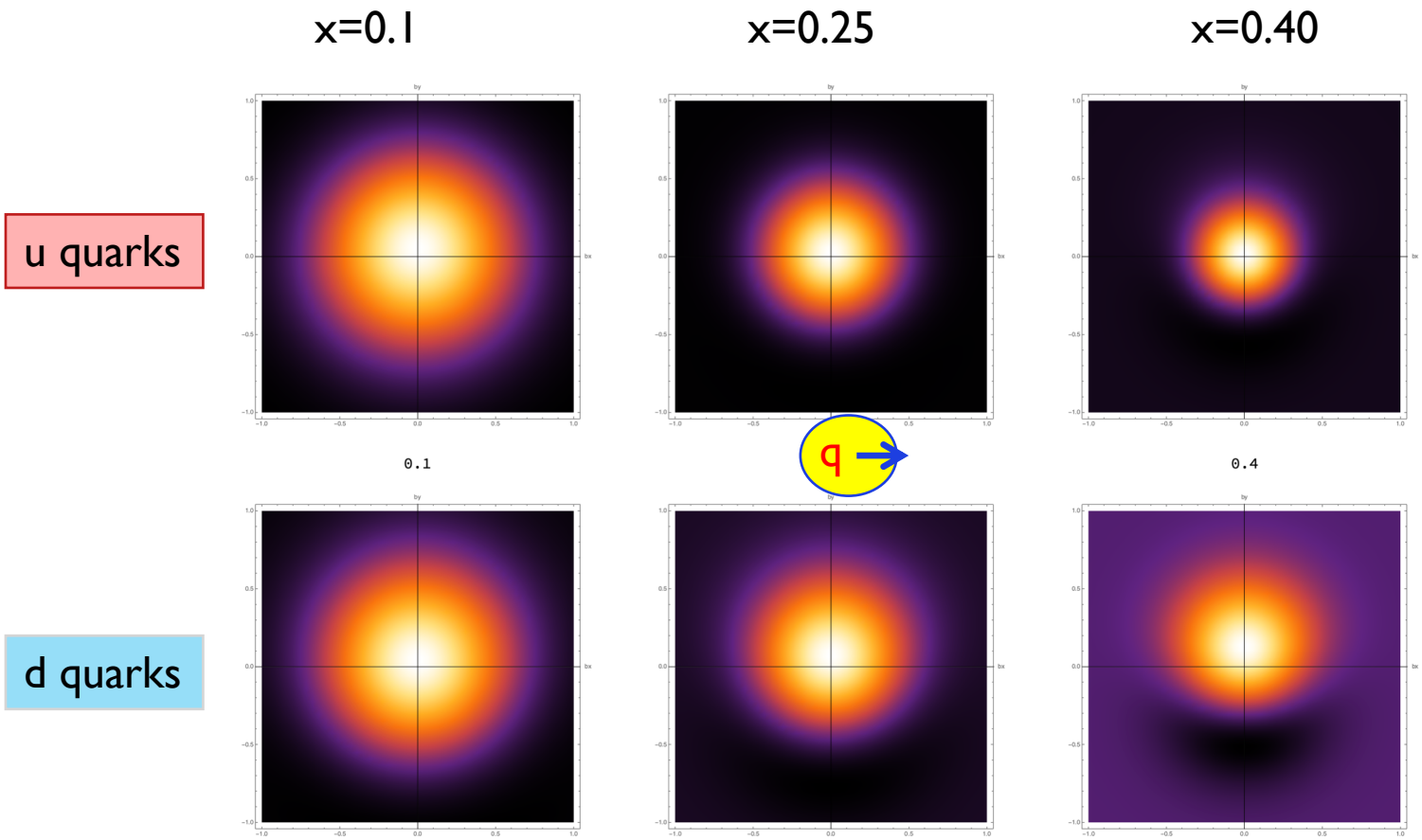
Lattice calculations

Controlled by E

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

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

Transverse Densities for Polarized Quarks in Unpolarized Proton



Note distortions for transversely polarized u and d quarks.

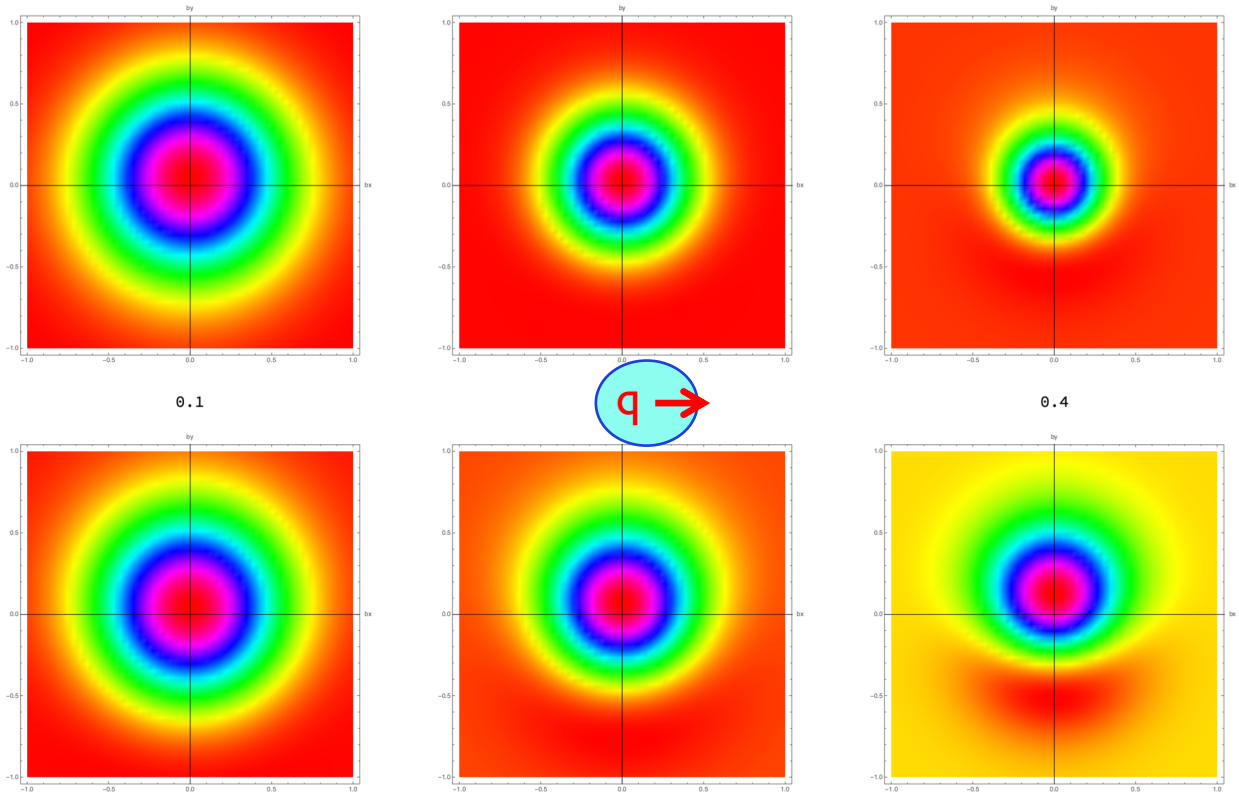
Quark polarization along x-axis q

Transverse Densities for Polarized Quarks in Unpolarized Proton

x=0.1 x=0.25 x=0.40

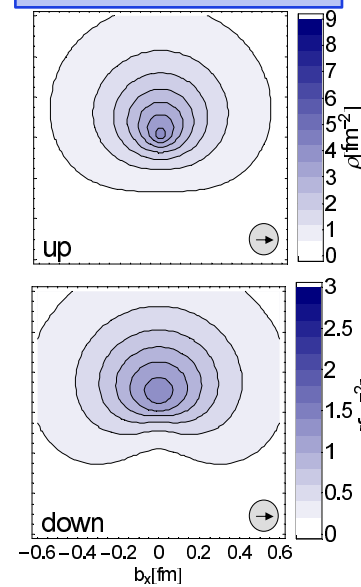
u quarks

d quarks



q →

- Lattice
- Integrated over x



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

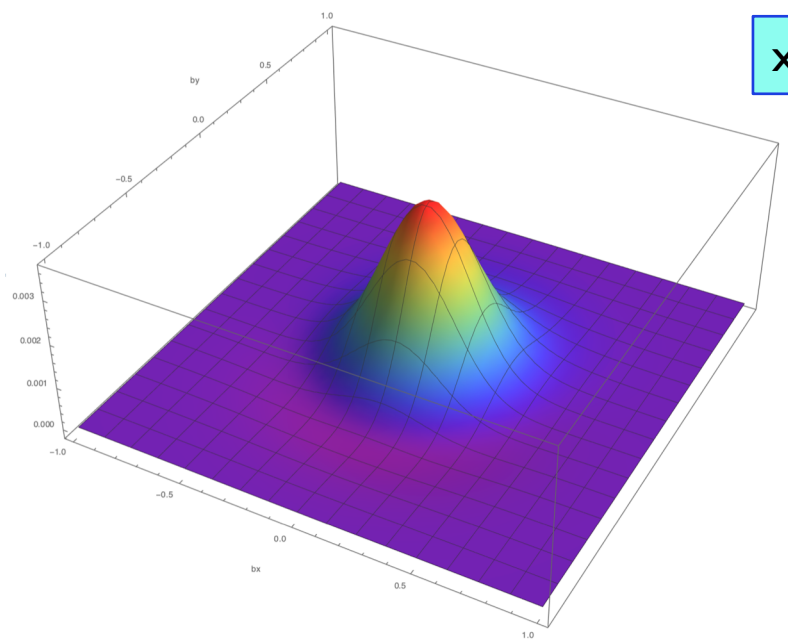
Quark polarization along x-axis q →

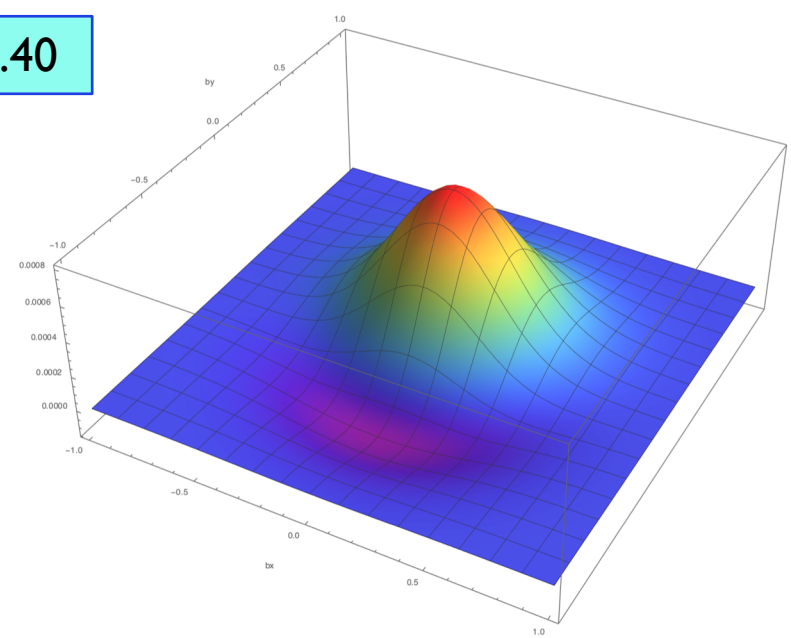
Transverse Densities for Polarized Quarks in Unpolarized Proton

u-quark density

d-quark density

x=0.40





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

CLAS12

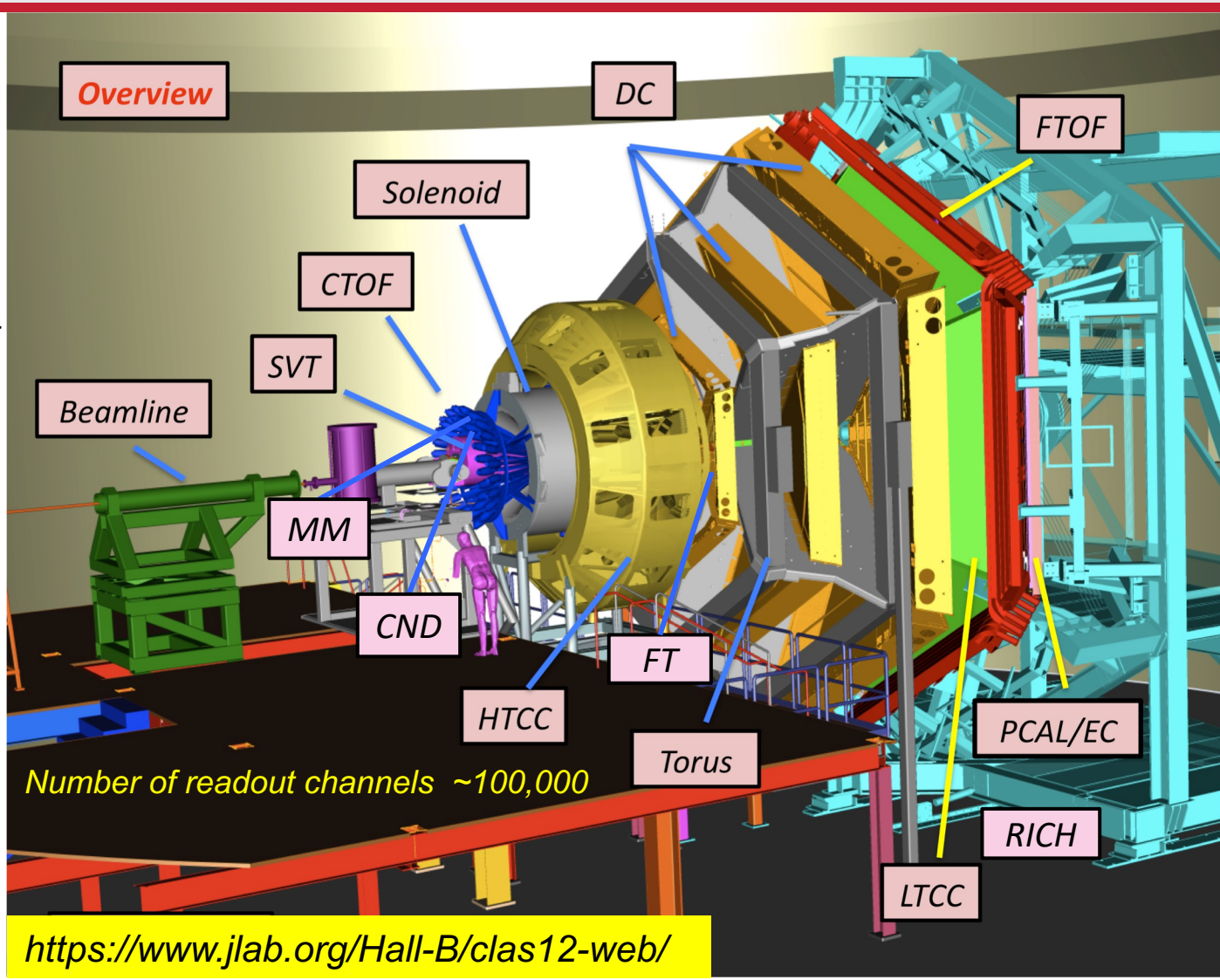
Central Detector:

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

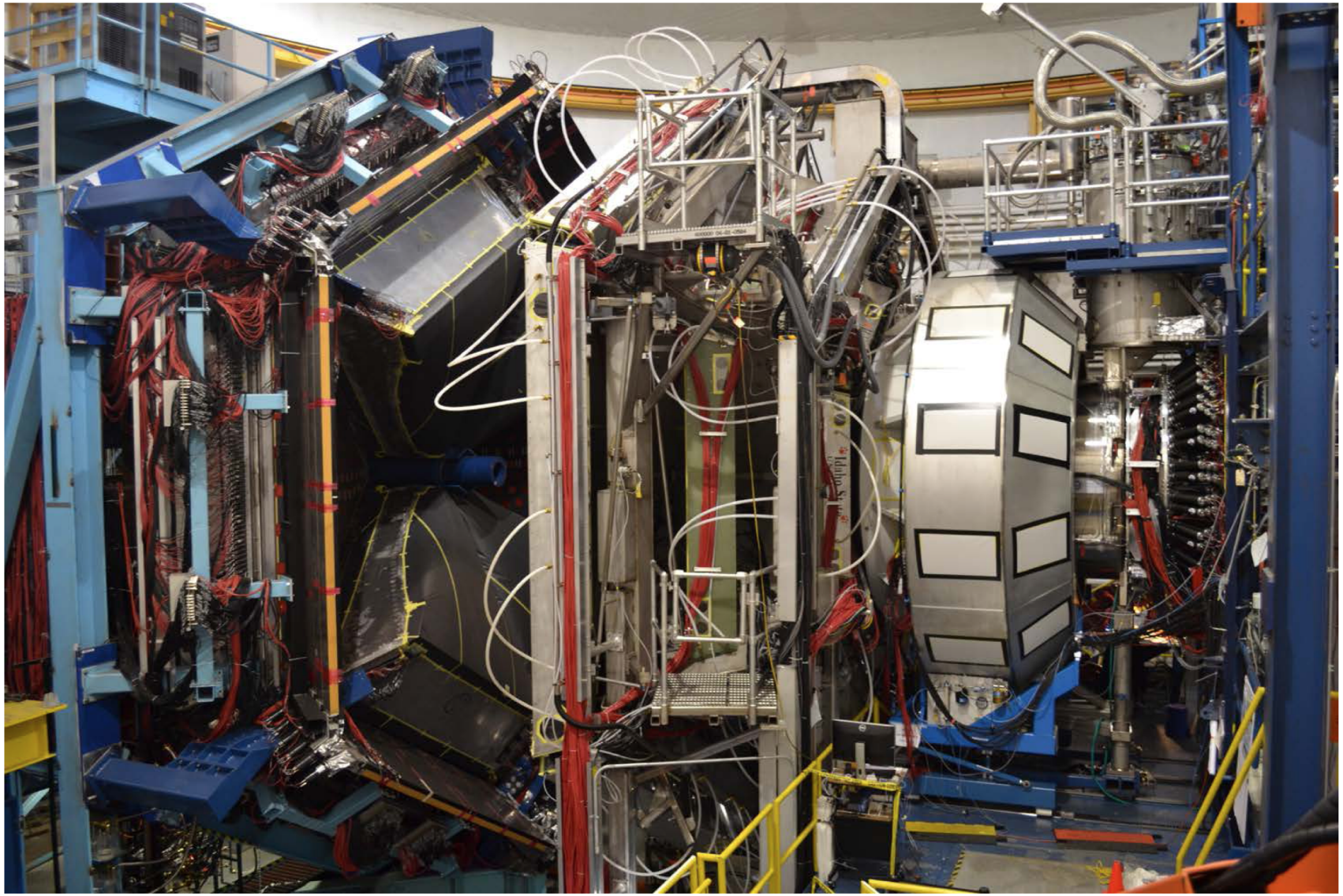
Forward Detector:

- *TORUS magnet*
- *HT Cherenkov Counter*
- *Drift chamber system*
- *LT Cherenkov Counter*
- *RICH detector (25K channels)*
- *Forward ToF System*
- *Preshower calorimeter*
- *E.M. calorimeter (EC)*

Forward Tagger *(FD)*



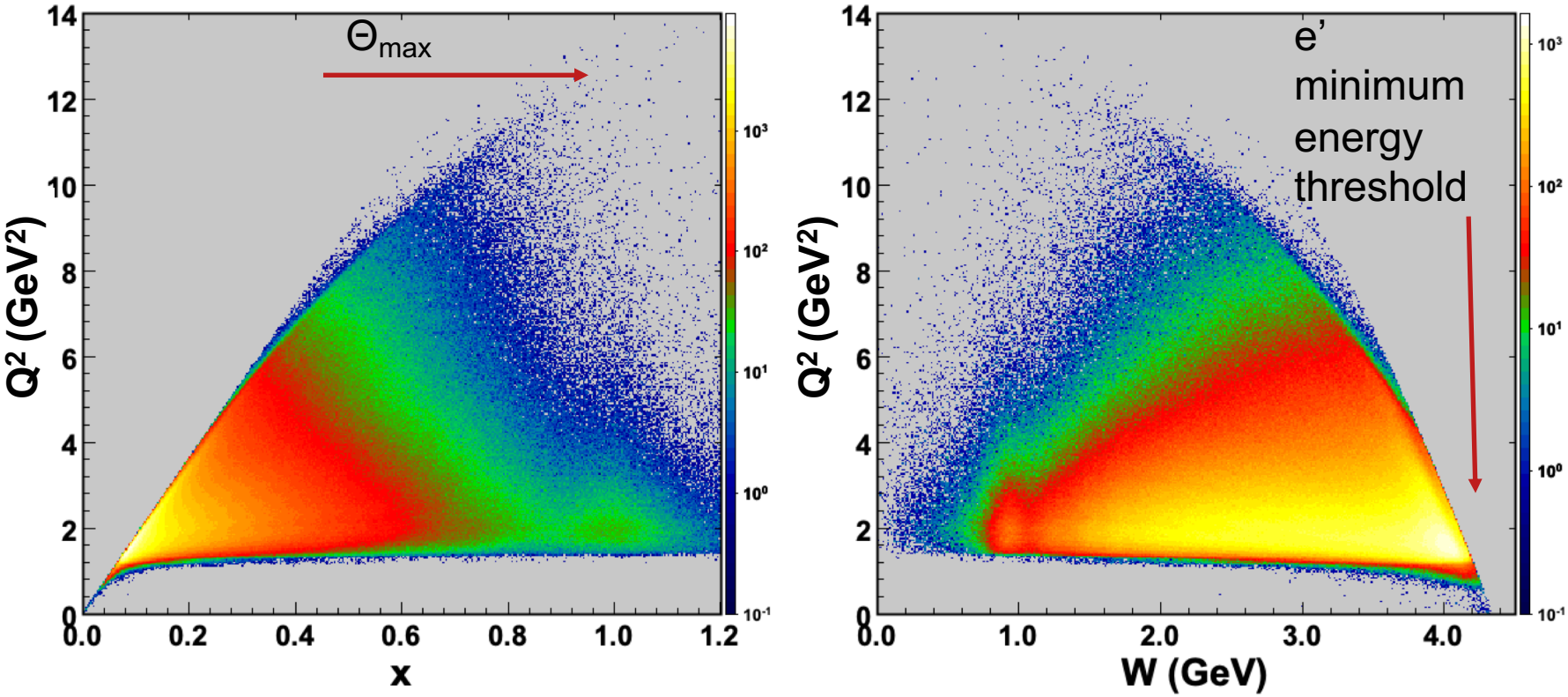
CLAS12 installed in Hall-B



CLAS12 kinematic reach

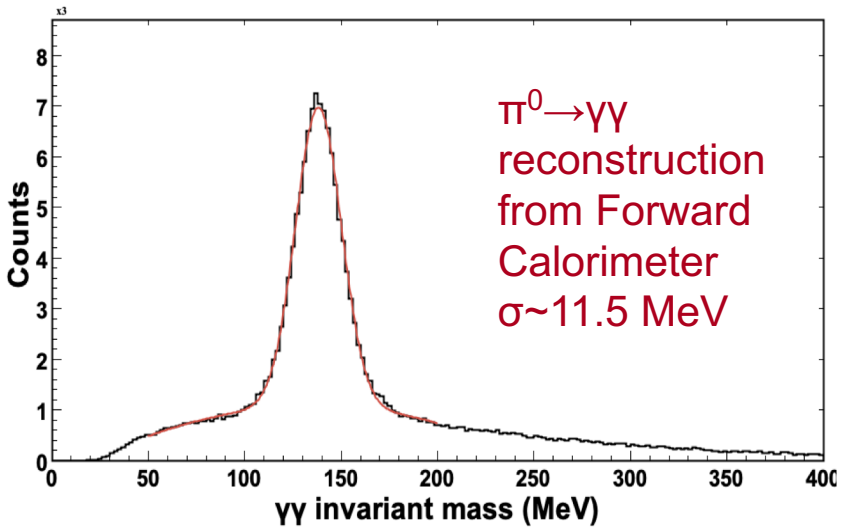
Beam energy at 10.6 GeV Torus current 3770 A, electrons in-bending, Solenoid magnet at 2416 A.

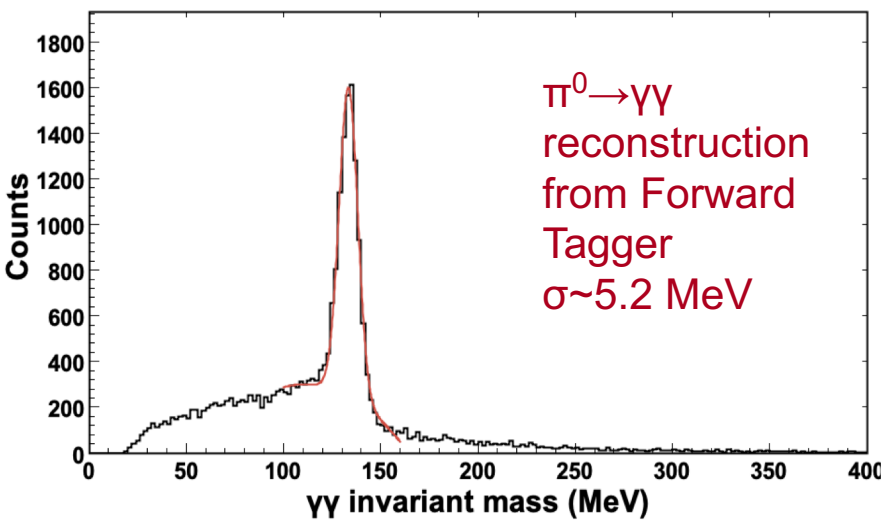
p(e,e')X

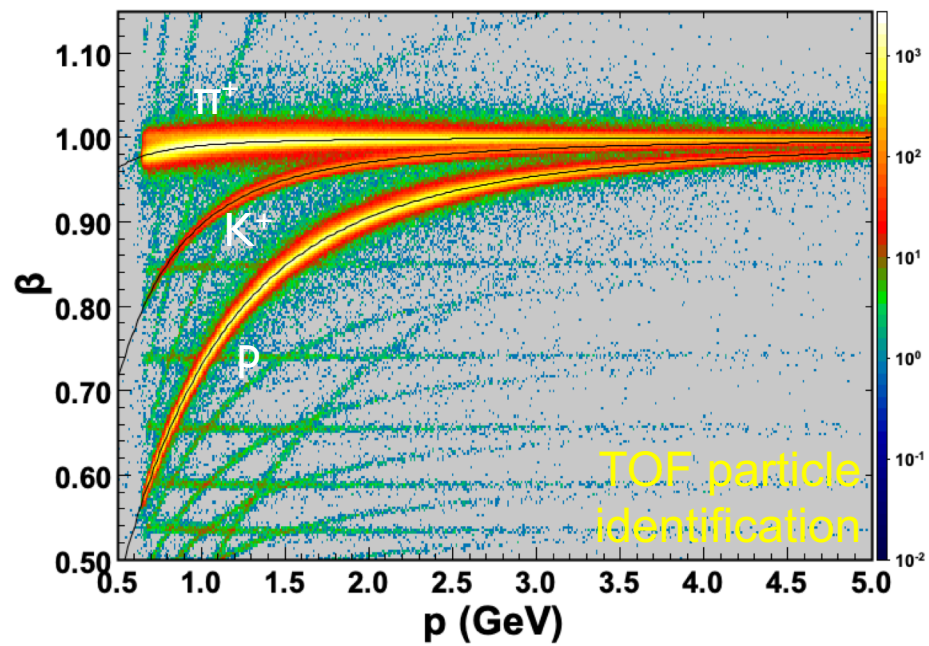


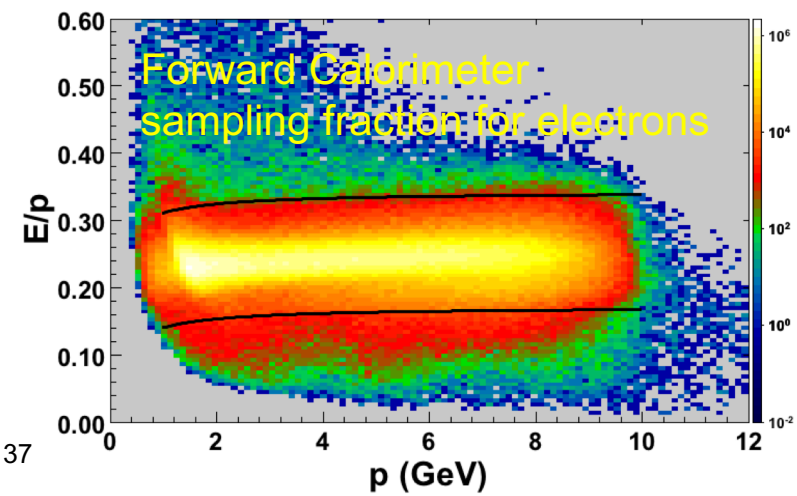
Plots based on 200 min. of data taking

Event reconstruction









CALS12: Coming soon

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

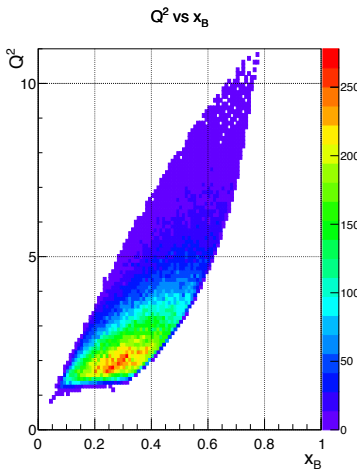
- Cross sections:
  - $ep \to ep(\pi^0, \eta)$
  - $en \to en(\pi^0, \eta)$
  - $ep \to e\pi^+ n$
  - $ep \to eK^+\Lambda$

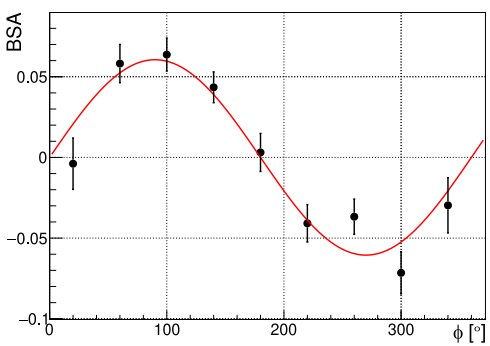
- Asymmetries:

$$\mathcal{A}_{LU} \; - \; beam\ spin$$
$$\mathcal{A}_{UL} \; - \; target\ spin$$
$$\mathcal{A}_{LL} \; - \; beam\ target$$

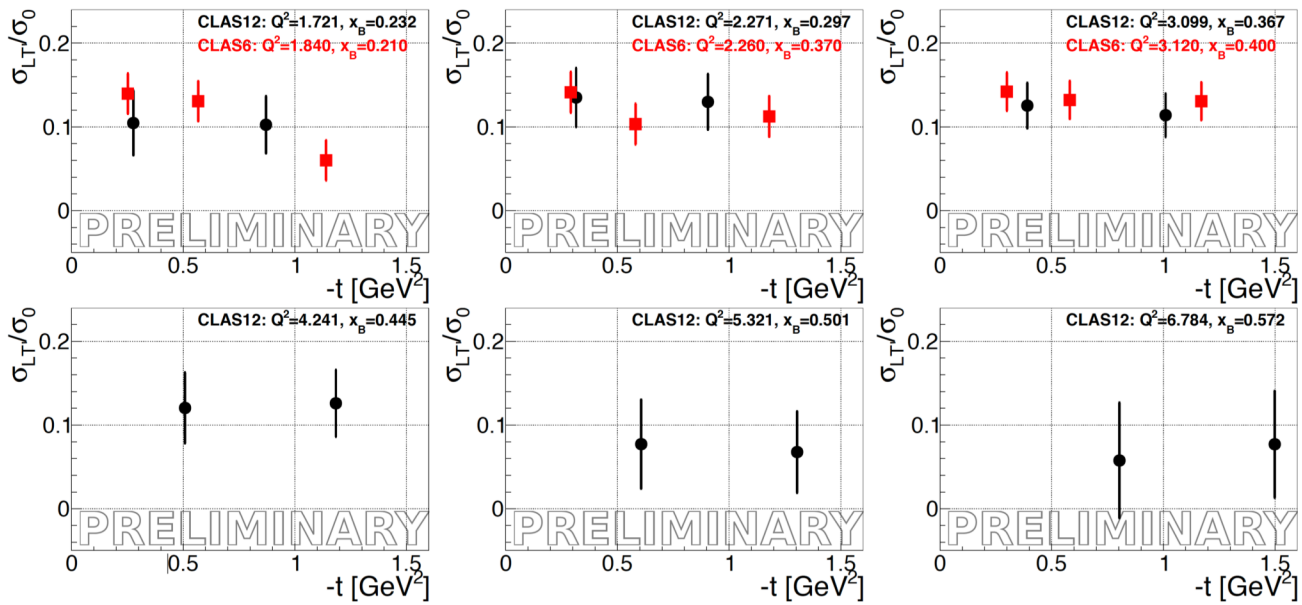
CLAS12 BSA

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





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



- The preliminary results are compatible with previous measurements

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 out of proton and neutron data 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 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.