MESON 2021

16th International Workshop on Meson Physics

May 17 - 20, 2021

Krakau (online)

# Exploring the 3D nucleon structure with CLAS and CLAS12 at JLAB

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

UNIVERSITY OF CONNECTICUT 1881

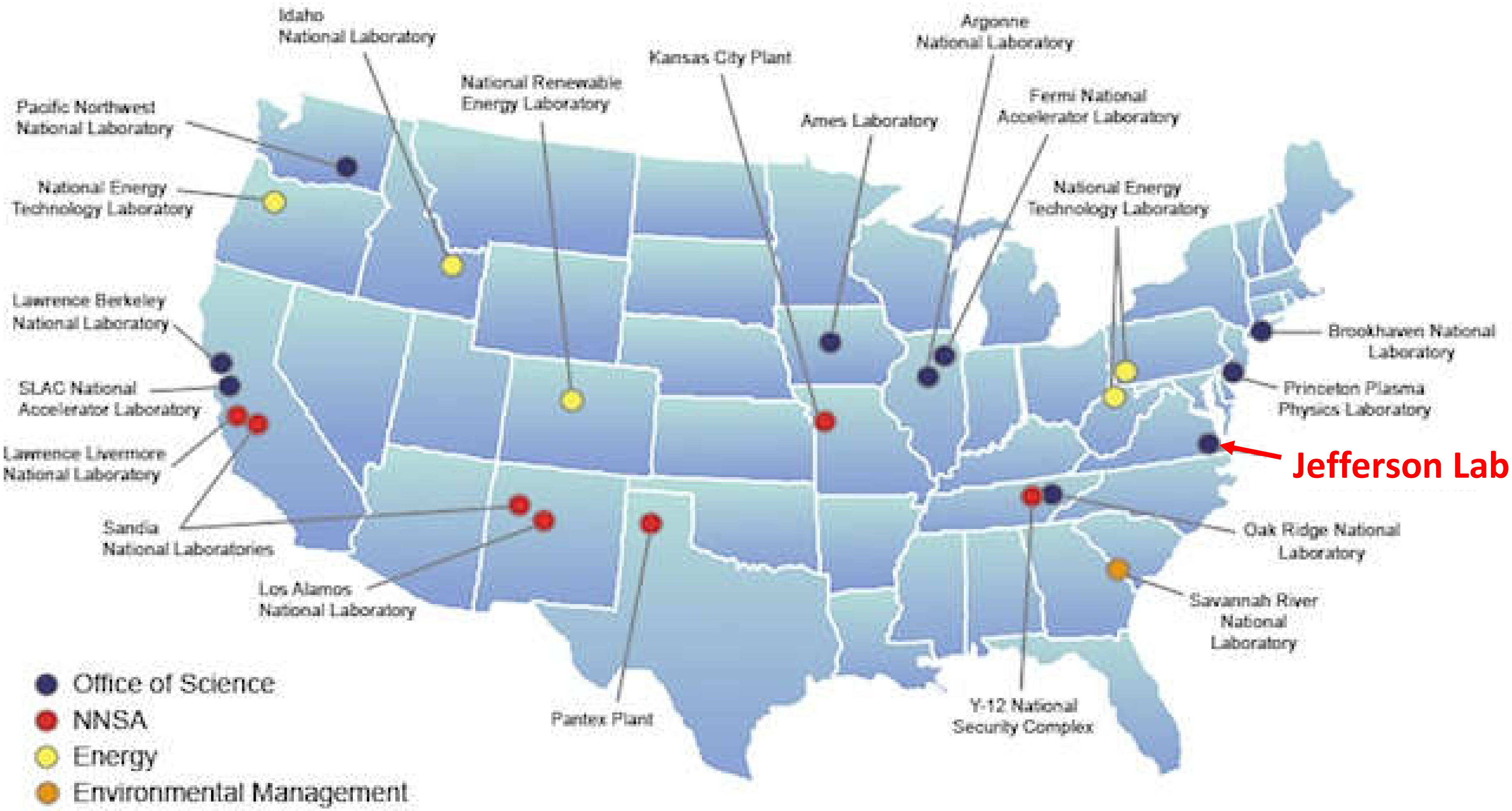
Stefan Diehl

*Justus Liebig University Giessen*

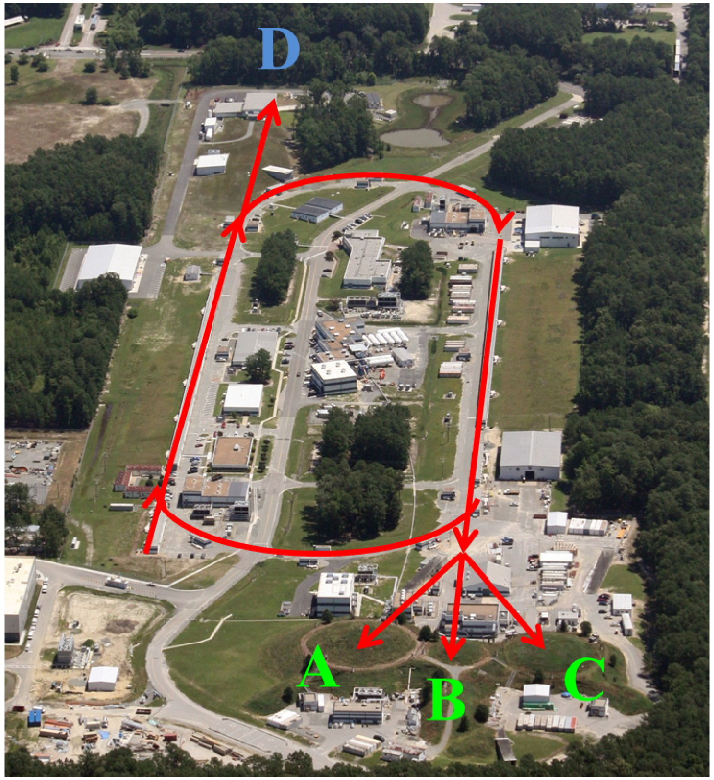
*University of Connecticut*

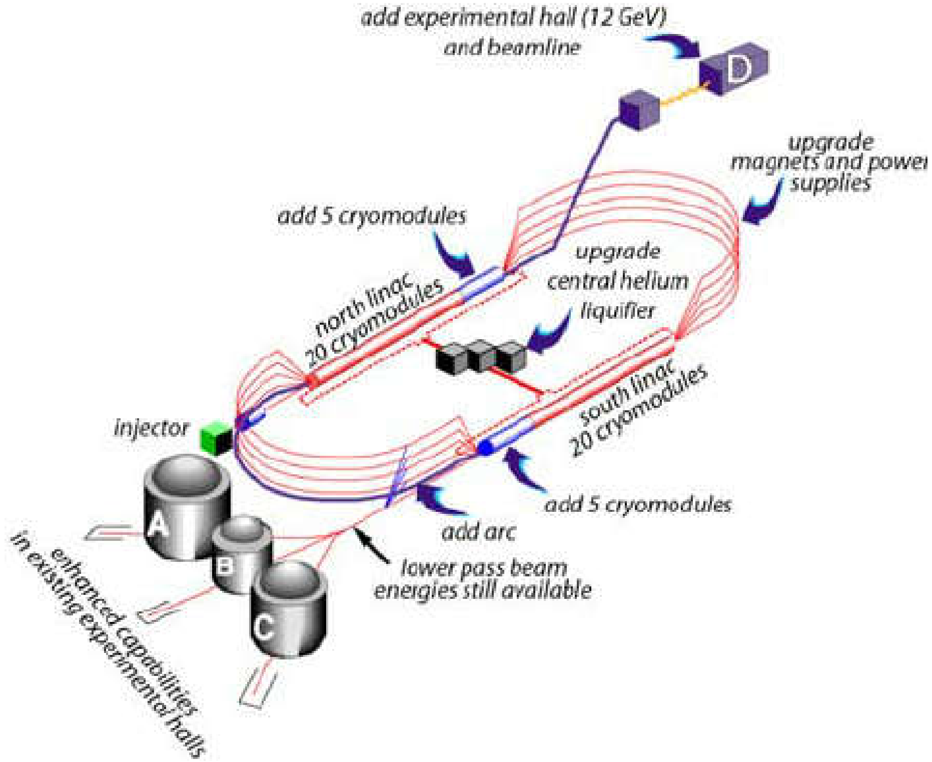
May 19, 2021

# Thomas Jefferson National Accelerator Facility (Jefferson Lab)



# Thomas Jefferson National Accelerator Facility (Jefferson Lab)



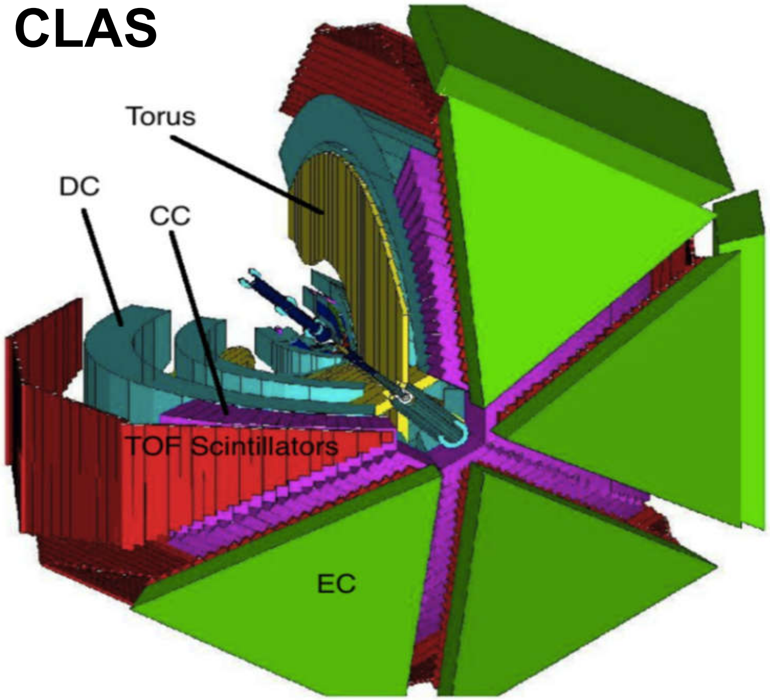



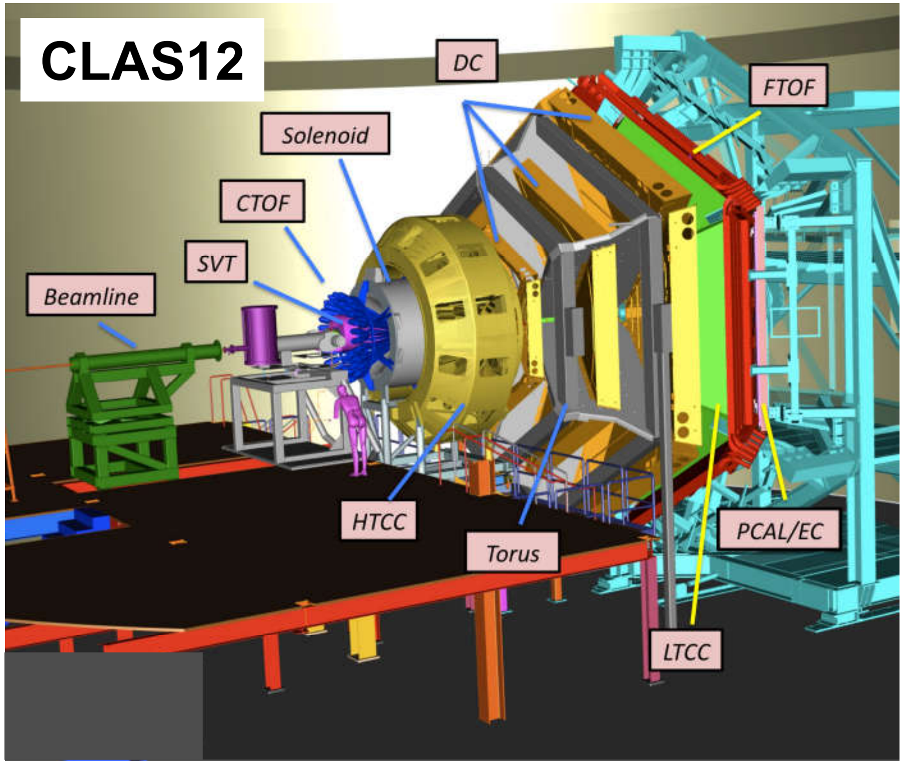

- CEBAF Upgrade completed in September 2017
  - → electron beam
  - → $E_{max}$ = 12 GeV
  - → $I_{max}$ = 90 μA
  - → $Pol_{max}$ ~ 90%

**Physics Operation**

- 4 halls running simultaneously since January 2018
- World-record for polarized electron beams

# CLAS / CLAS12 in Hall B at Jefferson Lab




- $\mathcal{L} = 1 \times 10^{35}$ cm$^{-2}$s$^{-1}$
- Inclusive electron trigger (all reactions will be analyzed in parallel)

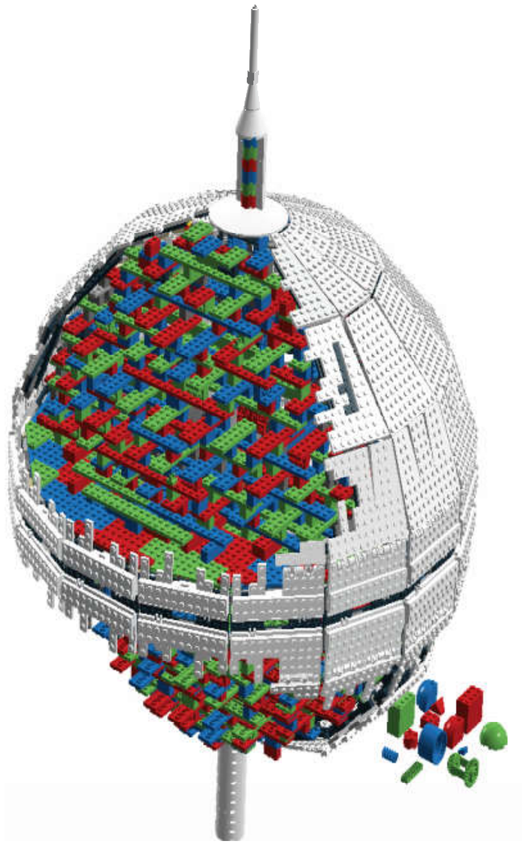
# QCD Science Questions

**How are the quarks and gluons, and their intrinsic spins distributed in space & momentum inside the nucleon?**

How can we recover the well-known characterics of the nucleon from the properties of its **colored building blocks**?

Mass?
Spin?
Charge?
...

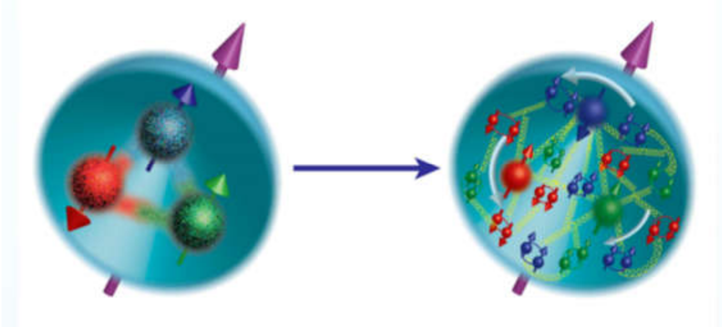
What are the relevant **effective degrees of freedom** and **effective interaction** at large distance?



**What is the role of orbital angular motion?**

# The Incomplete Nucleon: Spin Puzzle

- Proton has spin-1/2
- Proton is a composite system consisting of spin-1/2 quarks and spin-1 gluons



$$J_N = \frac{1}{2} = \frac{1}{2}\Sigma_q + L_q + J_g$$

➔ Sum of angular momentum of quarks and gluons together must be 1/2

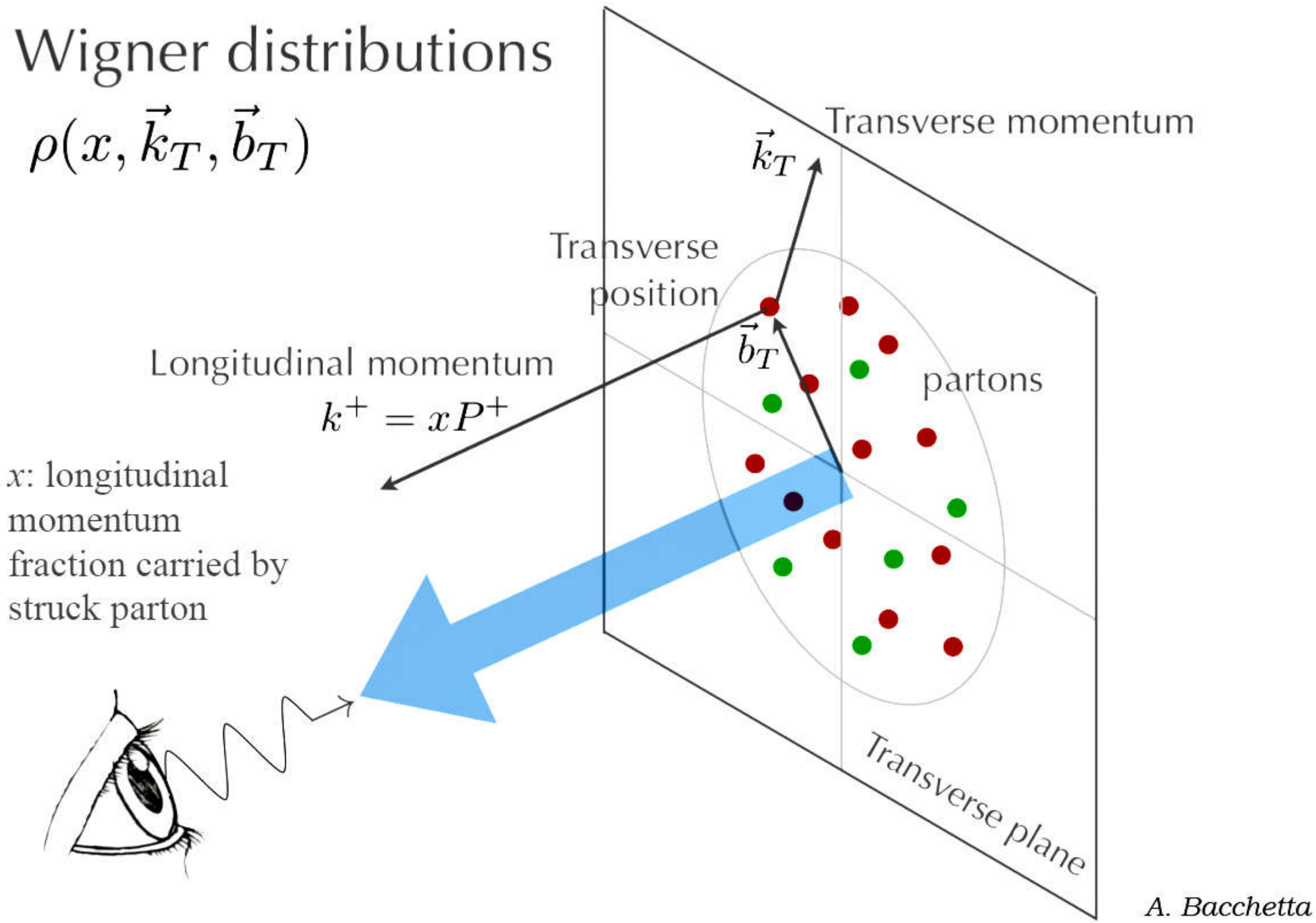
Possible contributions Quark spin, Quark orbital momentum
Gluon spin, Gluon orbital momentum

Classical: L ~ **r** x **p**

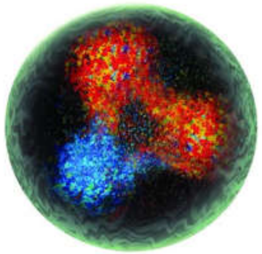
Needs a cross-product or something three-dimensional!

**We need to investigate the 3D nucleon structure!**

# 3-Dimensional Imaging of Quarks and Gluons



# 3-Dimensional Imaging of Quarks and Gluons



*Wigner function: full phase space parton distribution of the nucleon*

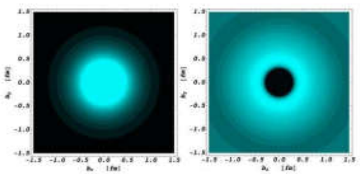
$\int d^2k_T$ → Generalised Parton Distributions (GPDs)

$\int d^2b_T$ → Transverse Momentum Distributions (TMDs)

Generalised Parton Distributions (GPDs): $\int dx$ → Form Factors *eg*: $G_E$, $G_M$

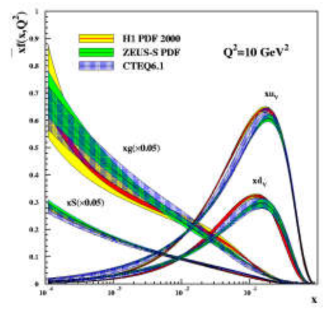
Generalised Parton Distributions (GPDs): $\int d^2b_T$ → Parton Distribution Functions (PDFs)

Transverse Momentum Distributions (TMDs): $\int d^2k_T$ → Parton Distribution Functions (PDFs)



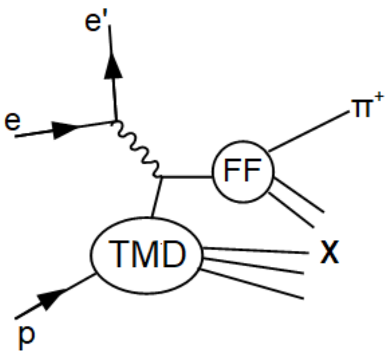
Form Factors
*eg*: $G_{E,}$ $G_M$

Parton Distribution Functions (PDFs)



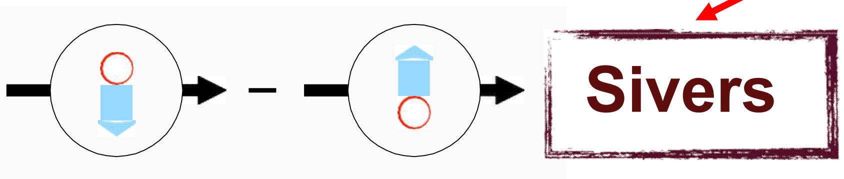
# Transverse Momentum Distributions (TMDs)

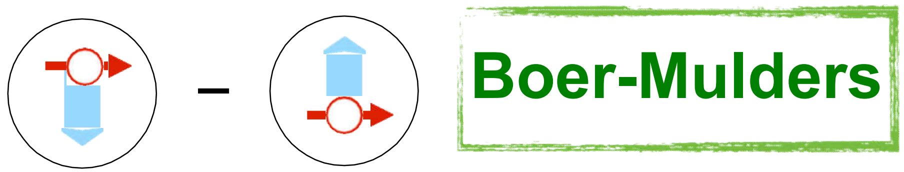
- Spin-dependent 3D momentum space images from semi-inclusive scattering




**quark pol.** / **nucleon pol.**

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h^{\perp}_1$ |
| L | | $g_1$ | $h^{\perp}_{1L}$ |
| T | $f^{\perp}_{1T}$ | $g_{1T}$ | $h_1$, $h^{\perp}_{1T}$ |




➔ Unpolarized quark distribution inside a transversly polarized proton

➔ Net polarization in direction i carried by the partons inside an unpolarized proton

# Semi-Inclusive Deep Inelastic Scattering (SIDIS)

$$F_{UU,T}(x, z, P_{h\perp}^2, Q^2)$$

$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Bigg\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}$$

$$+\lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big]$$

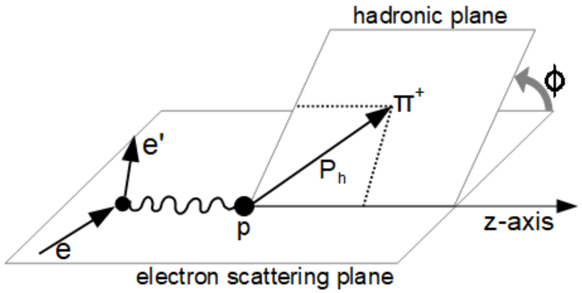
$$+S_L\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big]$$

$$+S_T\Big[\sin(\phi_h-\phi_S)\,\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}$$

$$+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}$$

$$+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}$$

$$+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Bigg\}$$




➔ **18 Structure Functions**

**EXPERIMENT:** Setting the proper beam and target polarization conditions (U, L, T)

# Longitudinally polarized beam and unpolarized target

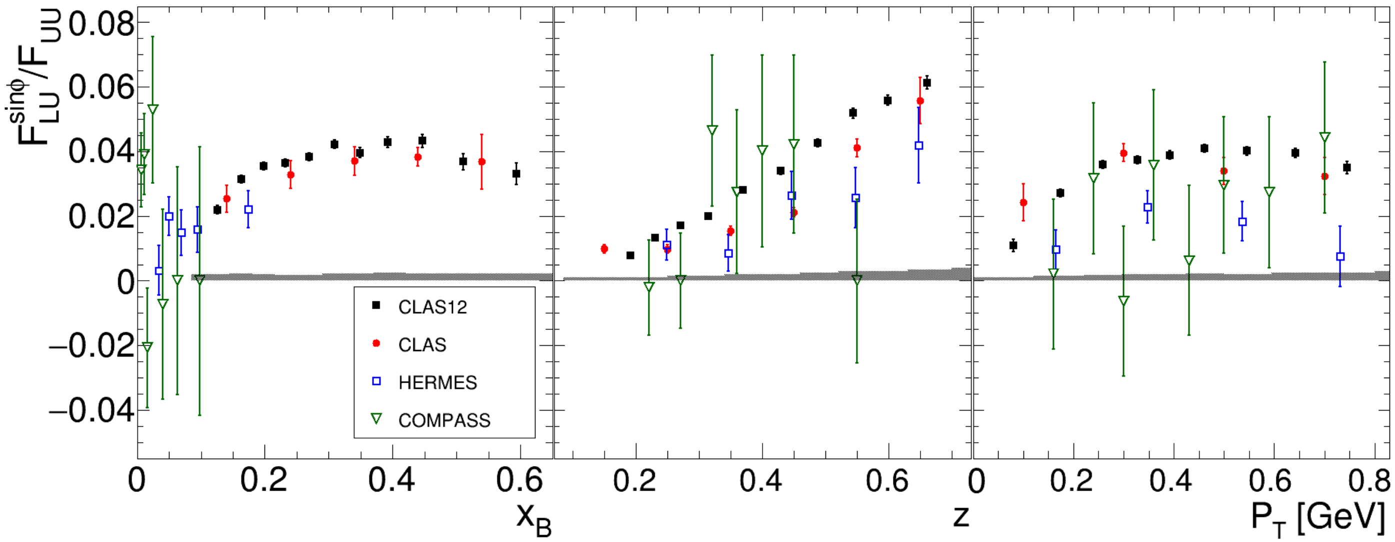
$$\frac{d\sigma}{dx_B\, dQ^2\, dz\, d\phi_h\, dp_{h\perp}^2} = K(x,y,Q^2)\Big\{F_{UU,T} + \varepsilon F_{UU,L}$$
$$+\sqrt{2\,\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}\Big\}$$

$$F_{LU}^{\sin\phi} = \frac{2M}{Q}\mathcal{C}\left(-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M_h}\left(xeH_1^\perp + \frac{M_h}{M}f_1\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p_T}}{M}\left(xg^\perp D_1 + \frac{M_h}{M}h_1^\perp\frac{\tilde{E}}{z}\right)\right)$$

twist-3 pdf, Collins FF, unpolarized dist. function, twist-3 FF, twist-3 t-odd dist. funcion, Boer-Mulders, twist-3 FF

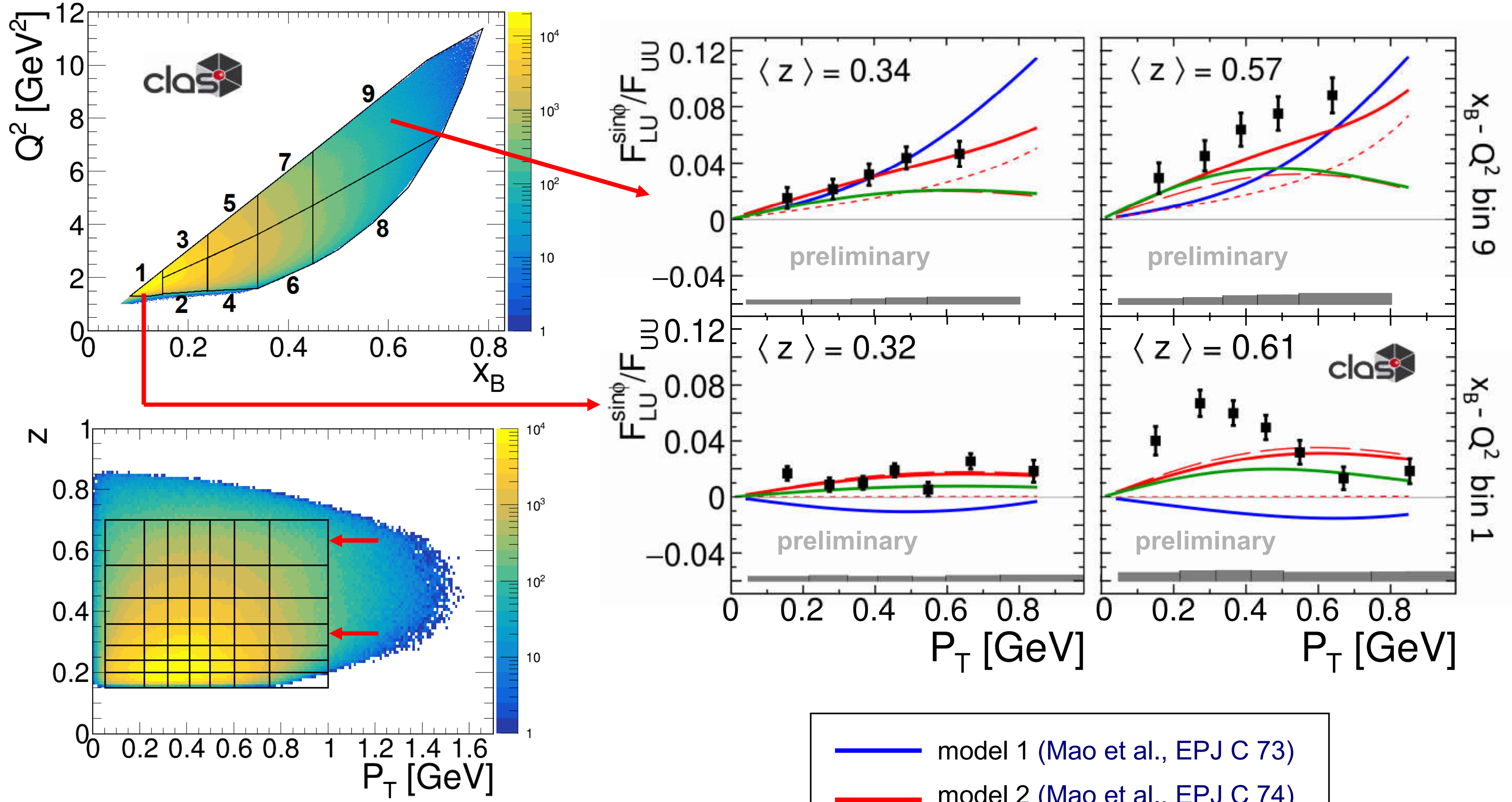
➔ TMD and Fragmentation Functions

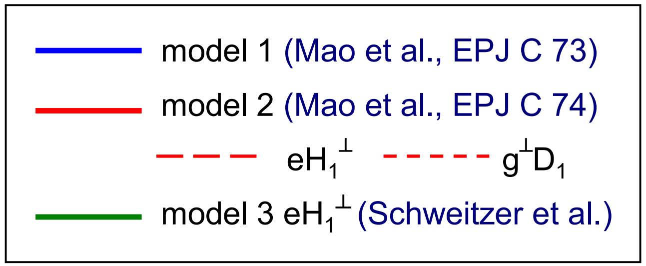
$\pi^+$




S. Diehl et. al (CLAS collab.), submitted to Phys. Rev. Lett., arXiv:2101.03544

# Multidimensional (4D) Single $\pi^+$ SIDIS with CLAS12



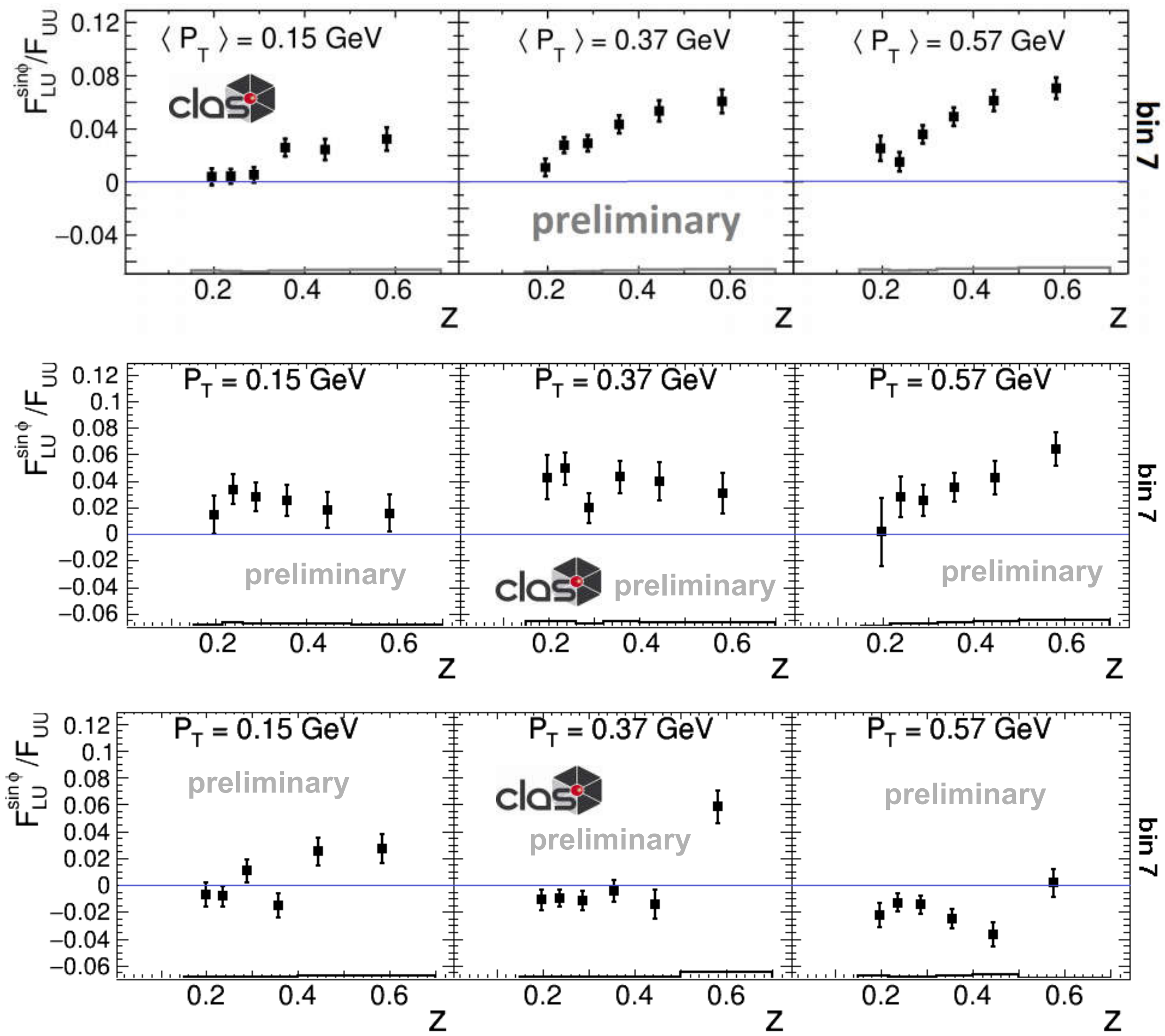

S. Diehl et. al (CLAS collab.), submitted to Phys. Rev. Lett., arXiv:2101.03544

# Multidimensional single $\pi^+$, $\pi^-$ and $\pi^0$ studies with CLAS12

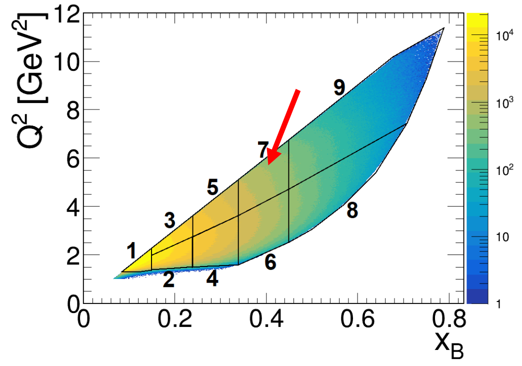
$\pi^+$

$\pi^0$

$\pi^-$




Q² = 4.8 GeV²
$x_B$ = 0.39




➔ Measurement of all 3 pions allows a flavor decomposition of TMDs and FFs

S. Diehl (JLU + UConn)

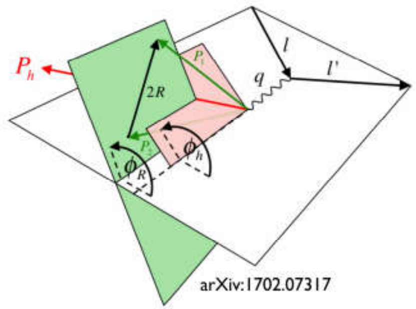
# Di-hadron SIDIS with CLAS12

Additional constraints can be obtained from **di-hadron SIDIS:**

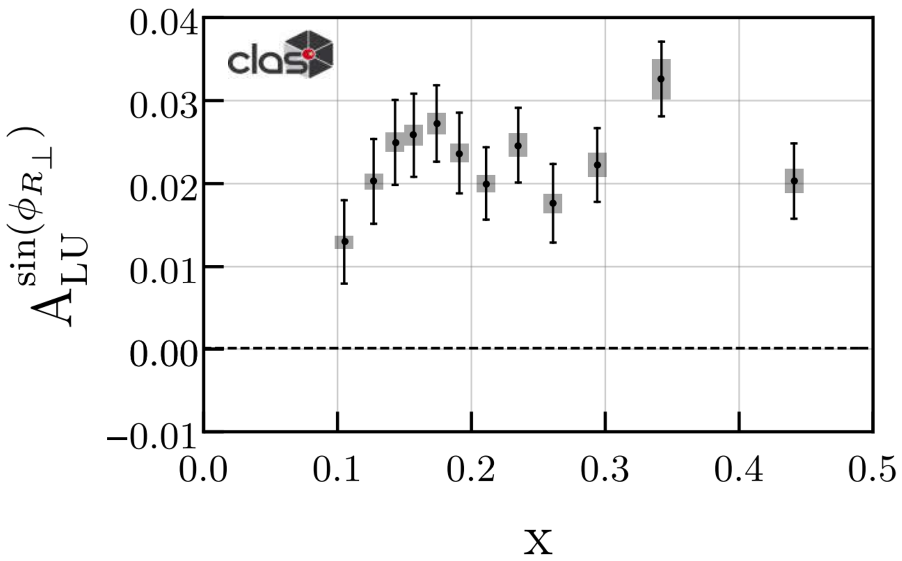
➔ ep → e`π⁺π⁻X provides a clean access to e(x) and the FF $G_1^{\perp}$

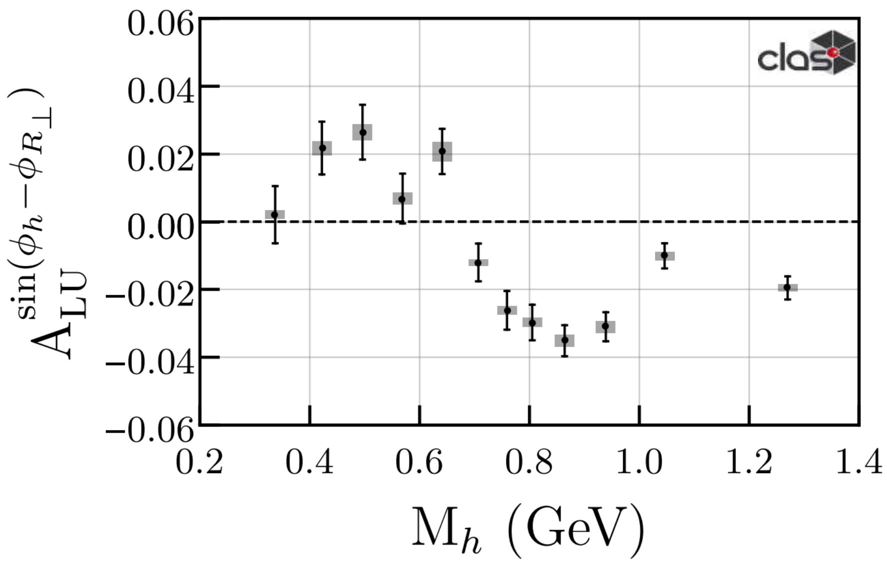
$$d\sigma_{LU} \propto W\lambda_e \sin(\phi_{R_\perp}) \left( x e(x) H_1^{\sphericalangle}(z, M_h) + \frac{1}{z} f_1(x) \tilde{G}^{\sphericalangle}(z, M_h) \right)$$

$$d\sigma_{LU} \propto C\lambda_e \sin(\phi_h - \phi_{R_\perp}) \mathcal{I}\left[f_1 G_1^{\perp}\right]$$




$\vec{P_h} = \vec{P_{\pi^+}} + \vec{P_{\pi^-}}$ $\vec{R} = \vec{P_{\pi^+}} - \vec{P_{\pi^-}}$




T. Hayward et. al (CLAS collab.), Phys. Rev. Lett. 126, 152501 (2021)

# Generalized Parton Distributions (GPDs)

$$W_{\Gamma}(\mathbf{r},k)=\frac{1}{2M_N}\int\frac{d^3\mathbf{q}}{(2\pi)^3}e^{-i\mathbf{q}\cdot\mathbf{r}}\left\langle\mathbf{q}/2\left|\hat{\mathcal{W}}_{\Gamma}(0,k)\right|-\mathbf{q}/2\right\rangle$$

↓

Integrate over transverse ***momentum*** space

↓

Generalized Parton Distributions (GPD)

↓

3-D nucleon images in the transverse coordinate and longitudinal momentum space

quark pol. (columns) / nucleon pol. (rows)

| N/q | $U$ | $L$ | $T$ |
|---|---|---|---|
| $U$ | $H$ | | $\bar{E}_T$ |
| $L$ | | $\widetilde{H}$ | $\widetilde{E}_T$ |
| $T$ | $E$ | $\widetilde{E}$ | $H_T, \widetilde{H}_T$ |

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

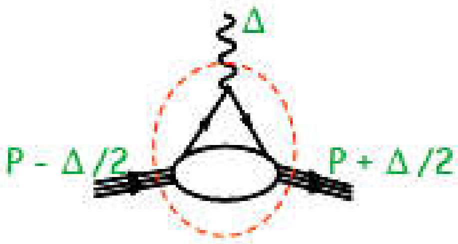
# Interpretation of GPDs in the kinematic limits

- in forward kinematics ($\xi$=0, t = 0) : **PDF limit**

$$H^q(x, \xi = 0, t = 0) = q(x)$$

$\xi \sim x_B/(2-x_B)$

- first moments of GPDs : **elastic form factor limit**




t = $\Delta^2$

$$\int_{-1}^{+1} dx H^q(x, \xi, t) = F_1^q(t)$$ → Dirac FF

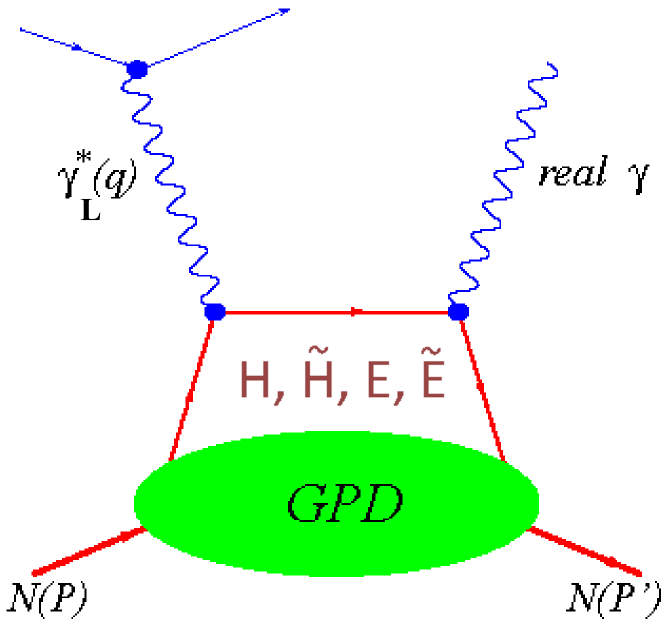
$$\int_{-1}^{+1} dx E^q(x, \xi, t) = F_2^q(t)$$ → Pauli FF

$$\int_{-1}^{+1} dx \tilde{H}^q(x, \xi, t) = G_A^q(t)$$ → axial FF

$$\int_{-1}^{+1} dx \tilde{E}^q(x, \xi, t) = G_P^q(t)$$ → pseudoscalar FF

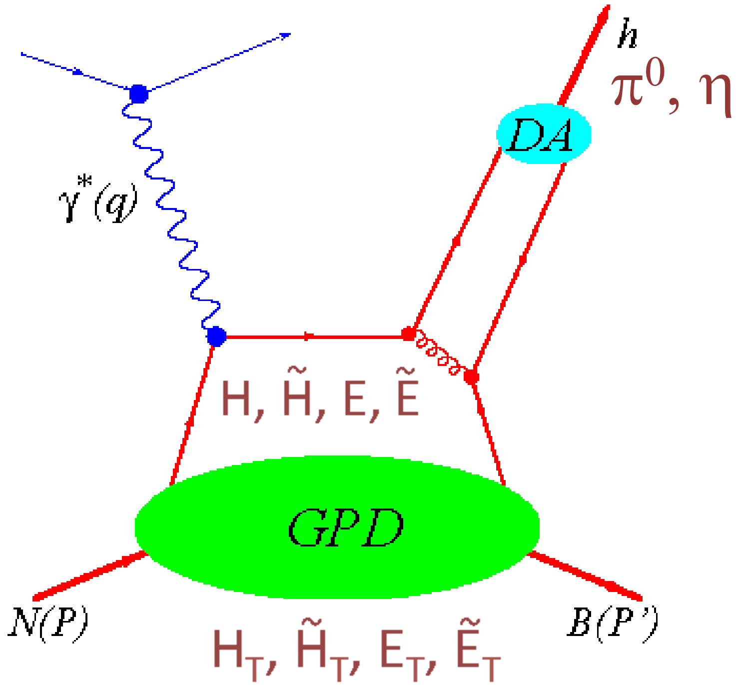
# Study GPDs: Deeply Virtual Exclusive Processes

## Deeply Virtual Compton Scattering (DVCS)




+ Clean process
- Only sensitive to chiral even GPDs

## Deeply Virtual Meson Production (DVMP)

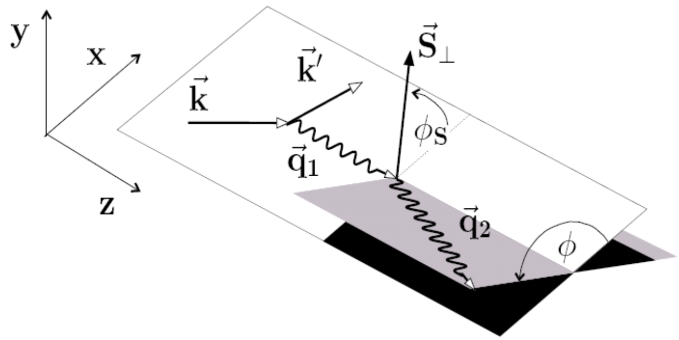



+ Enables Flavour decomposition of GPDs
+ Access to transversity degrees of freedom described by chiral-odd GPDs
- Distribution Amplitude (DA) is involved as additional soft non pert. quantity

# A path towards extracting GPDs

➔ Extraction via cross section σ and asymmetry measurements

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$




Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi \, \{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\} d\phi$$

➔ $H(\xi,t)$

Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi \, \{F_1 \tilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi)E)\} d\phi$$

➔ $\tilde{H}(\xi,t)$

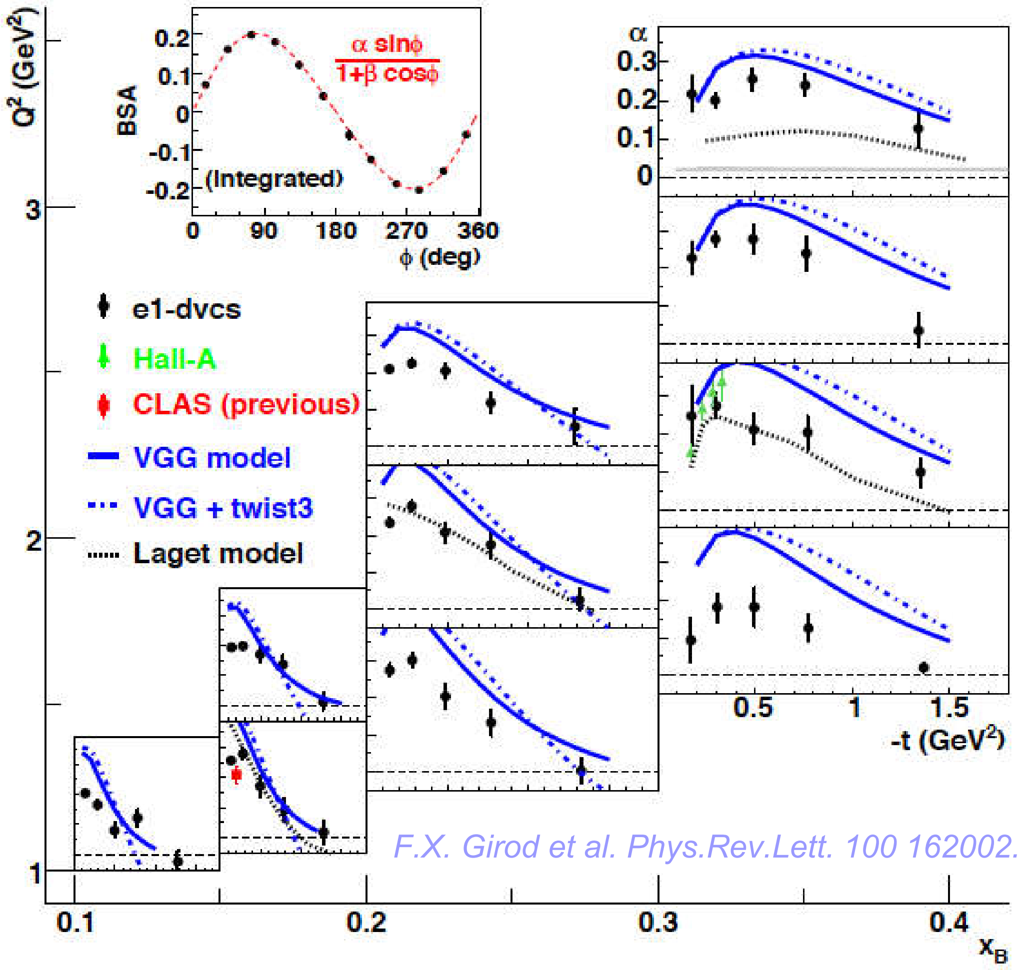
Unpolarized beam, transverse target:

$$\Delta\sigma_{UT} \sim \cos\phi \sin(\phi_s - \phi)\{k(F_2 H - F_1 E)\} d\phi$$

➔ $E(\xi,t)$

# DVCS Beam Spin Asymmetry

## CLAS at 6 GeV

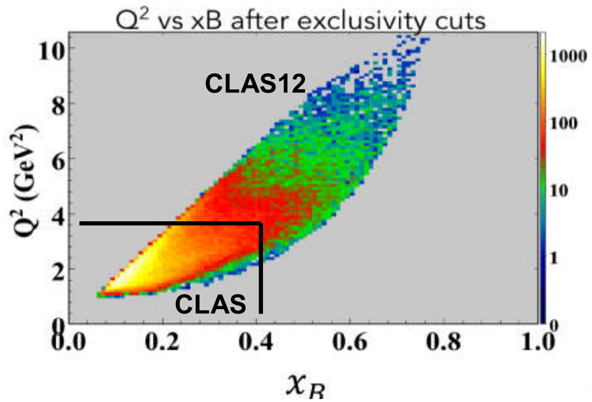


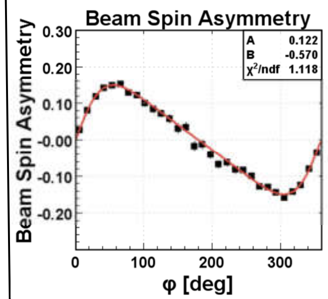

*F.X. Girod et al. Phys.Rev.Lett. 100 162002.*

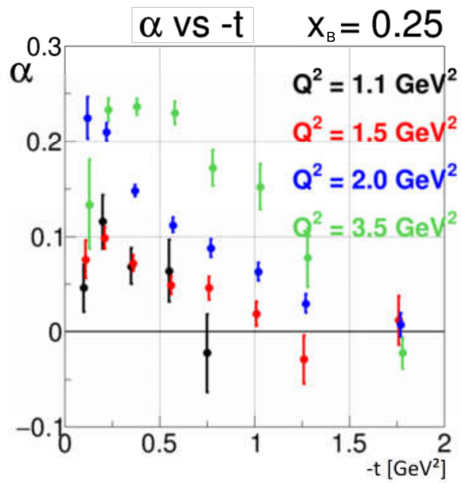
Precision in a large phase space $Q^2$, $x_B$, $t$

## CLAS12 at 10.6 GeV

- extended kinematic coverage
- increased statistics
- deuterium (neutron) target

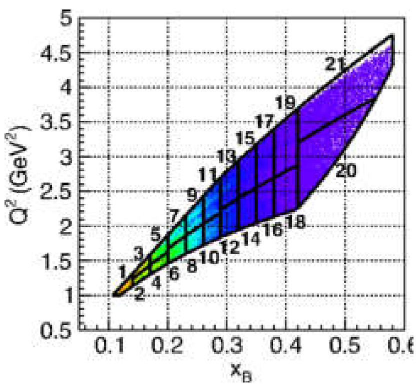


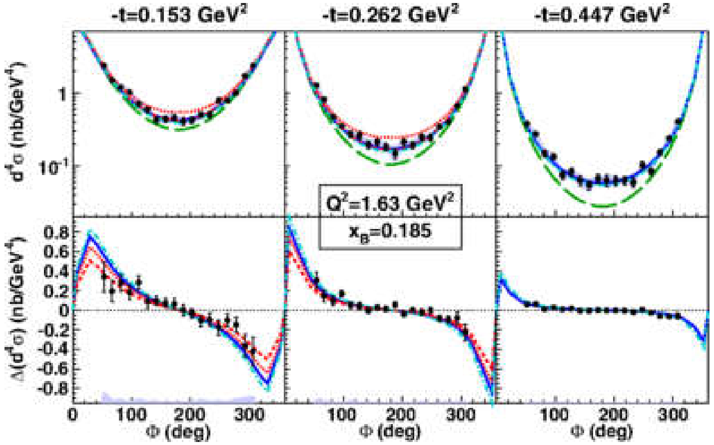



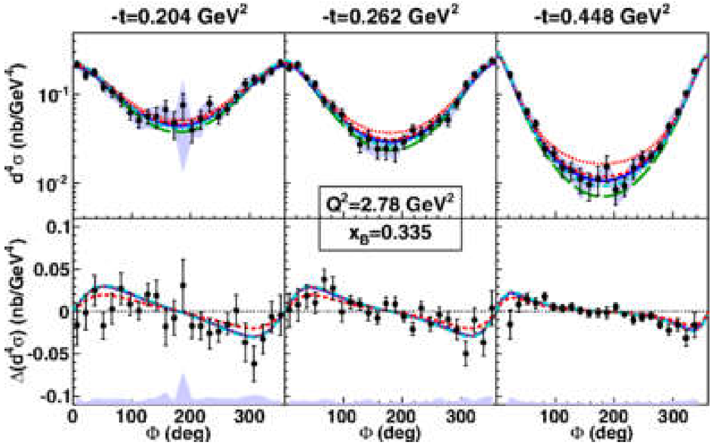



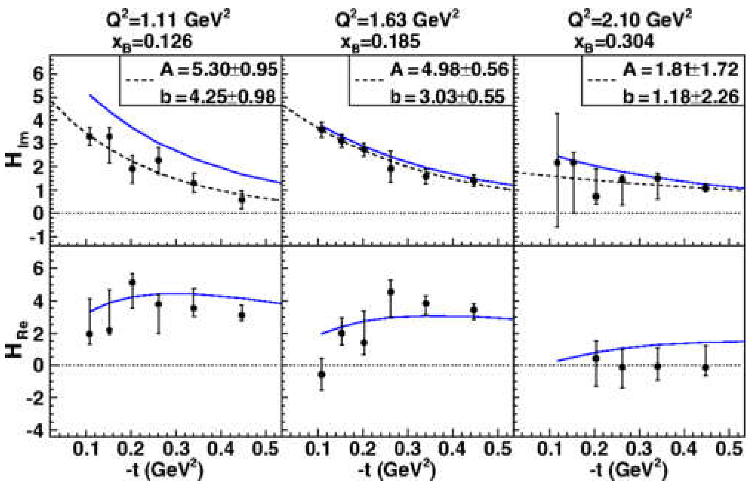

G. Christiaens

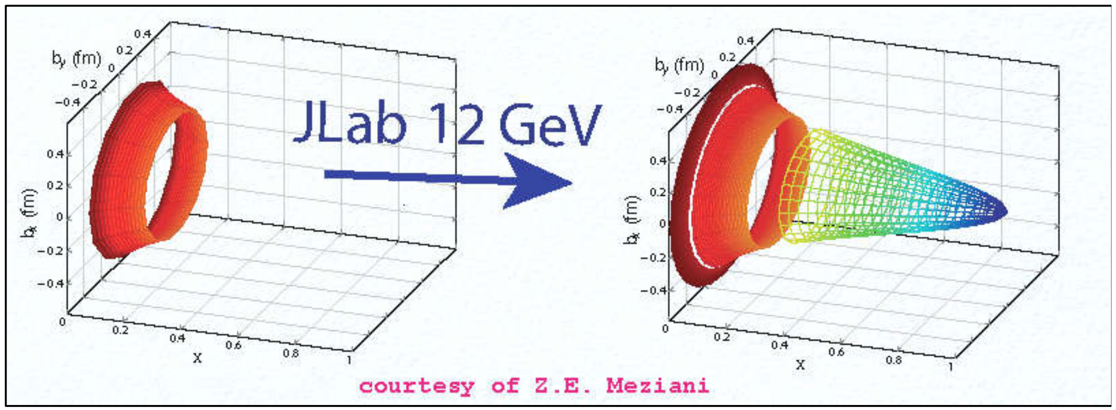
# DVCS Unpolarized Cross-Sections with 6 GeV CLAS




H. S. Jo *et al.* (CLAS Collaboration), Phys. Rev. Lett. 115, 212003 (2015)

# Imaging pressure within the nucleon

- GPDs provide indirect access to mechanical properties of the nucleon (encoded in gravitational form factors of the energy-momentum tensor)

X. D. Ji, PRD **55**, 7114-7125 (1997)    M. Polyakov, PLB **555**, 57-62 (2016)

<u>GFFs are related to GPDs via sum rules</u>:

$$\int x\,[H(x,\xi,t)+E(x,\xi,t)]\,dx = 2J(t)$$

angular momentum

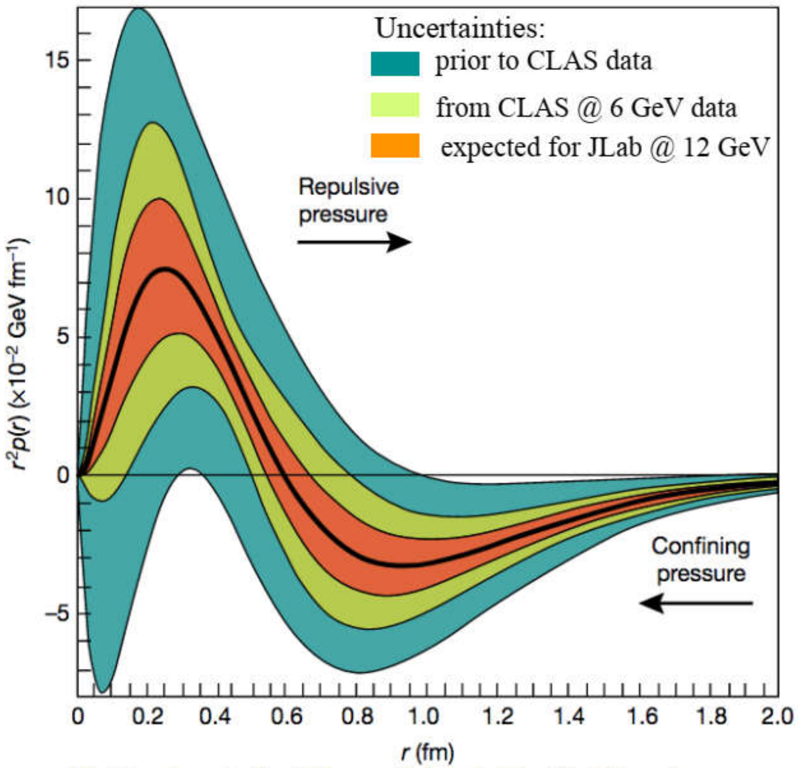
$$\int xH(x,\xi,t)dx = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$

mass

pressure and shear forces

➔ Posibility to extract pressure distributions

➔ More data needed to constrain the d-term

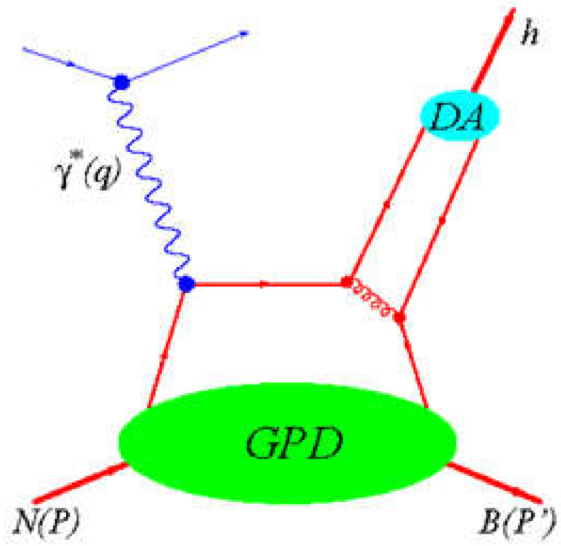



V. Burkert, L. Elouadrhiri, F.-X. Girod, Nature **557**, 396-399 (2018)

K. Kumerički, Nature **570**, E1-E2 (2019)

# Deeply Virtual Meson Production in the GPD regime

| | Meson | Flavor |
|---|---|---|
| $\mathcal{H}_T, \mathcal{E}_T$ | $\pi^+$ | $\Delta u - \Delta d$ |
| | $\pi^0$ | $2\Delta u + \Delta d$ |
| | $\eta$ | $2\Delta u - \Delta d + 2\Delta s$ |
| $\mathcal{H}, \mathcal{E}$ | $\rho^+$ | $u - d$ |
| | $\rho^0$ | $2u + d$ |
| | $\omega$ | $2u - d$ |
| | $\phi$ | $g$ |




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

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

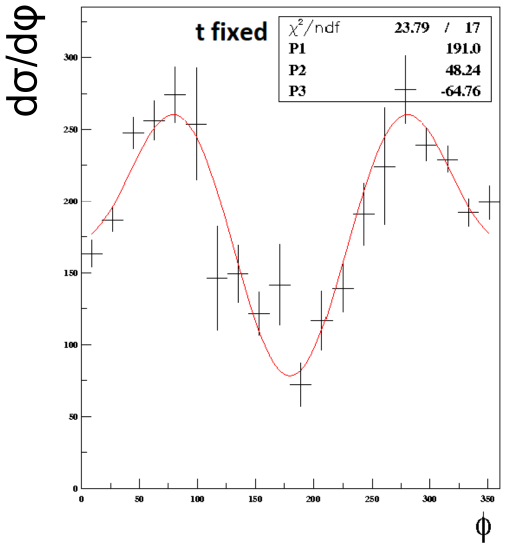
**$\bar{E}_T$ is related to the protons anomalous tensor magnetic moment**

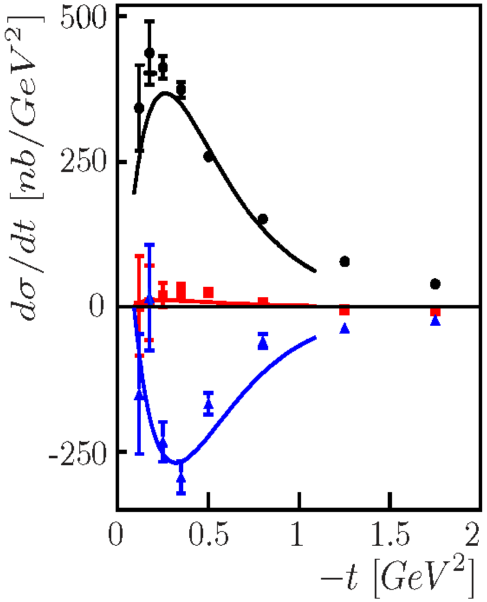
**$H_T$ is related to the protons tensor charge**

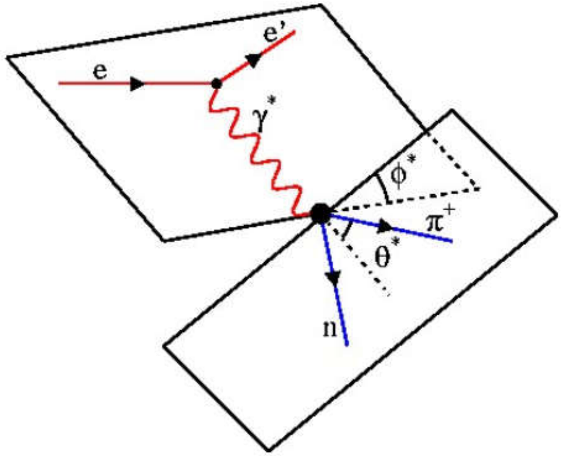
**➔ Absolute magnitude of transversly polarized valence quarks inside a transv. polarized nucleon**

# Differential Cross Sections for hard exclusive meson production

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



# CLAS data and GPD theory predictions

**2 theoretical models:**

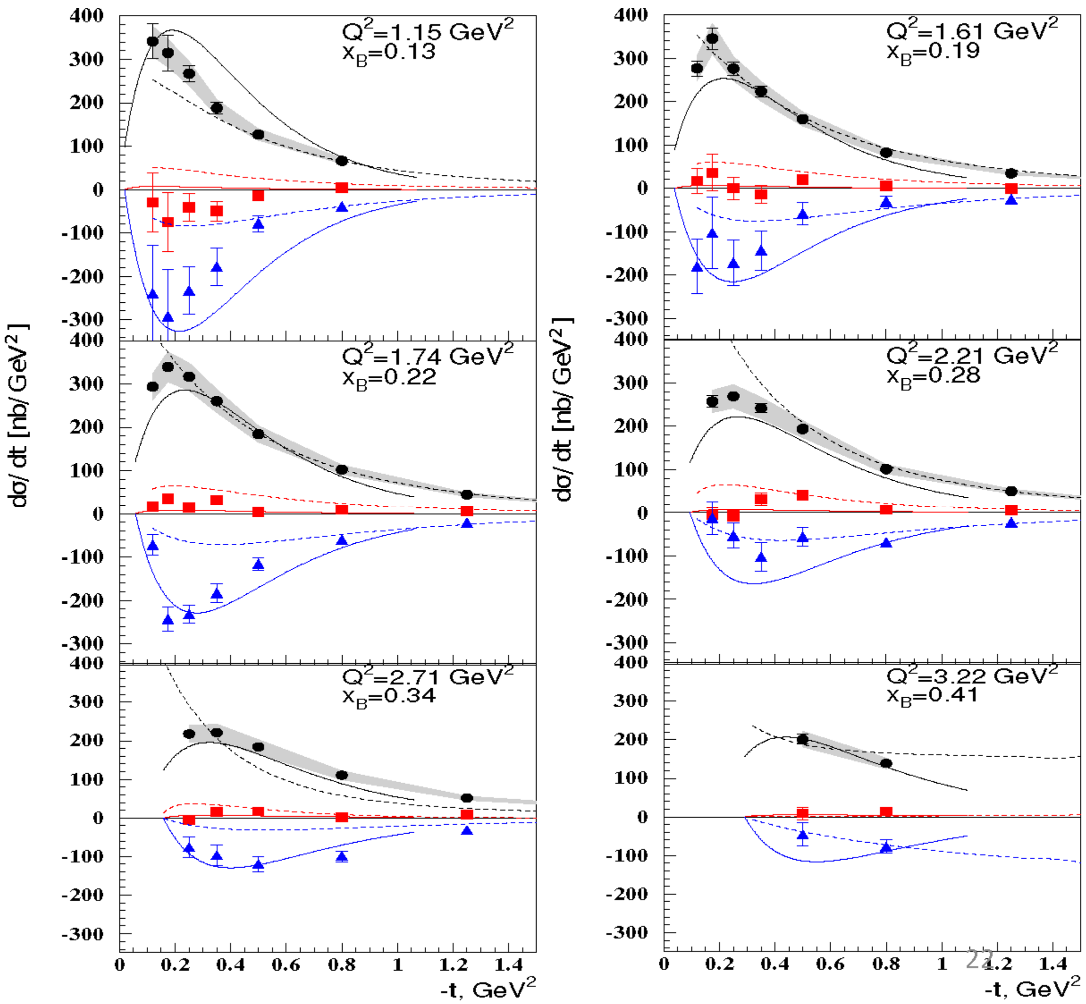
**Goloskokov, Kroll (GK)**
**Eur. Phys. J. A. 47: 112 (2011)**

→ GPDs parametrized based on data

**Goldstein, Hernandez, Liuti**
**Phys. Rev. D 84, 034007 (2011)**

→ Model allows flexible parametrization of GPDs

**e p → e p $\pi^0$**




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

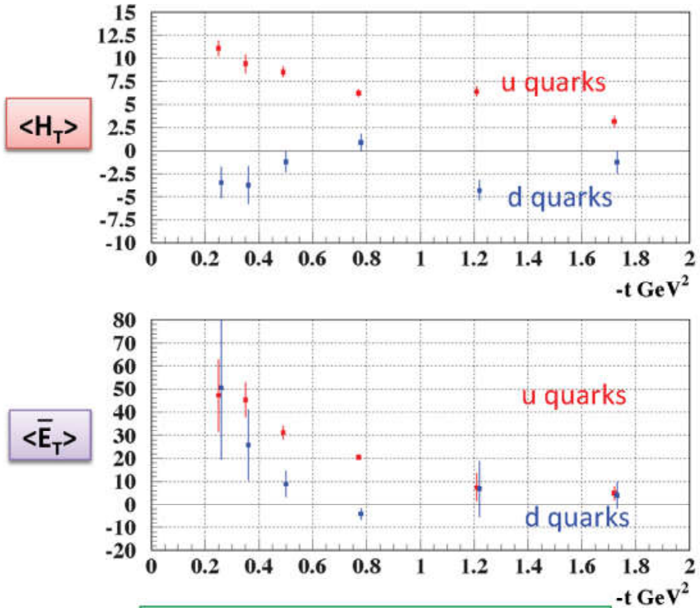
CLAS collaboration. I Bedlinskiy et al. Phys.Rev.Lett. 109 (2012) 112001

# Flavour Decomposition of GPDs and Transverse Quark Densities

- GPDs appear in different flavor combinations for $\pi^0$ and $\eta$

$$H_T^\pi = \frac{1}{3\sqrt{2}}[2H_T^u + H_T^d]$$
$$H_T^\eta = \frac{1}{\sqrt{6}}[2H_T^u - H_T^d]$$

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

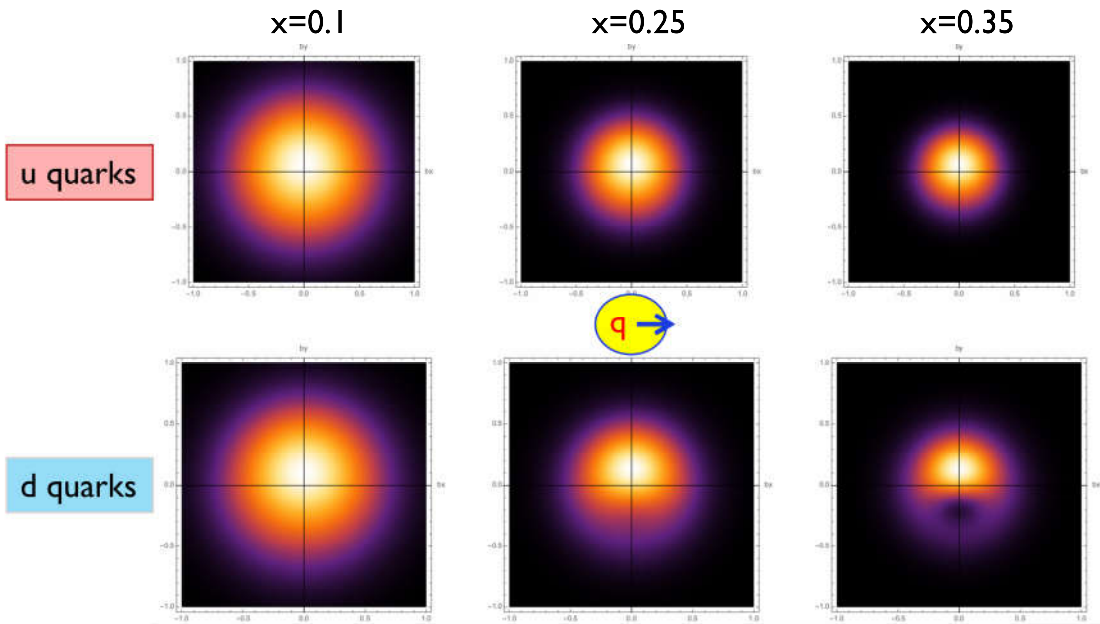



VK arXiv: 1601.04367 [hep-ex] 2016

**Transverse densities for pol. quarks in an unpol. proton**

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

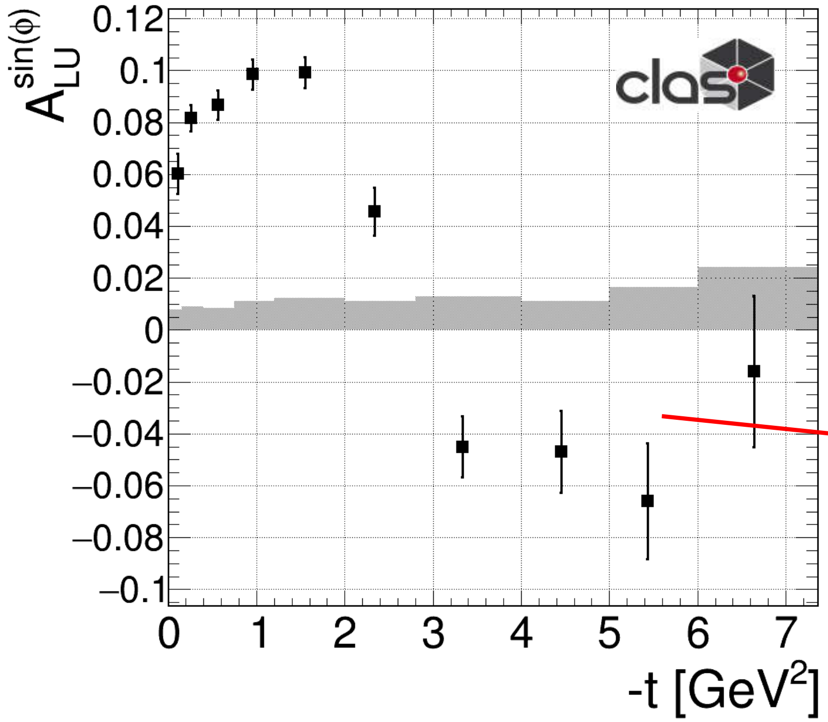
V. Kubarovsky (JLAB)

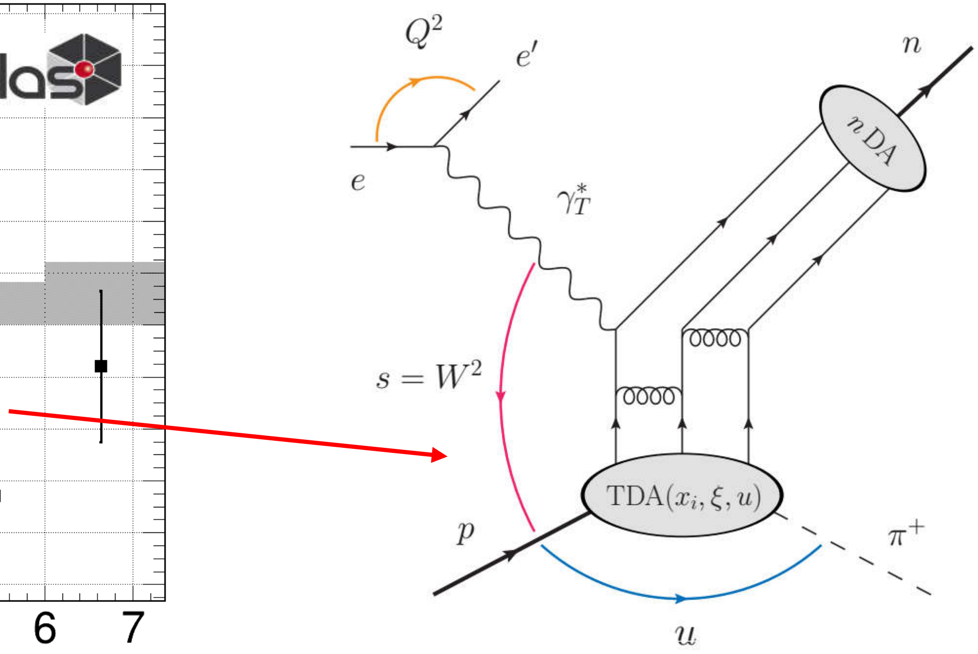


# Beam spin asymmetry for $ep \rightarrow en\pi^+$

$$BSA_i = \frac{1}{P_e} \cdot \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

$$BSA = \frac{A_{LU}^{\sin\phi} \sin\phi}{1 + A_{UU}^{\cos\phi} \cos\phi + A_{UU}^{\cos(2\phi)} \cos(2\phi)}$$



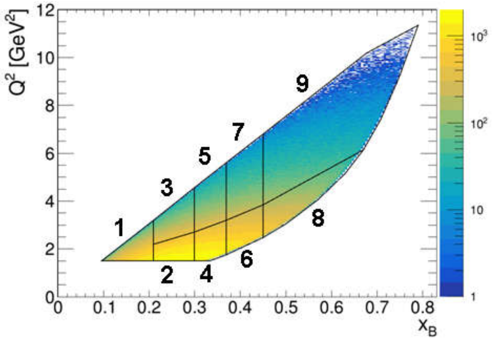

S. Diehl (JLU + UConn)

# $\sigma_{LT'}/\sigma_0$ for the hard exclusive $\pi^+$ channel with CLAS12

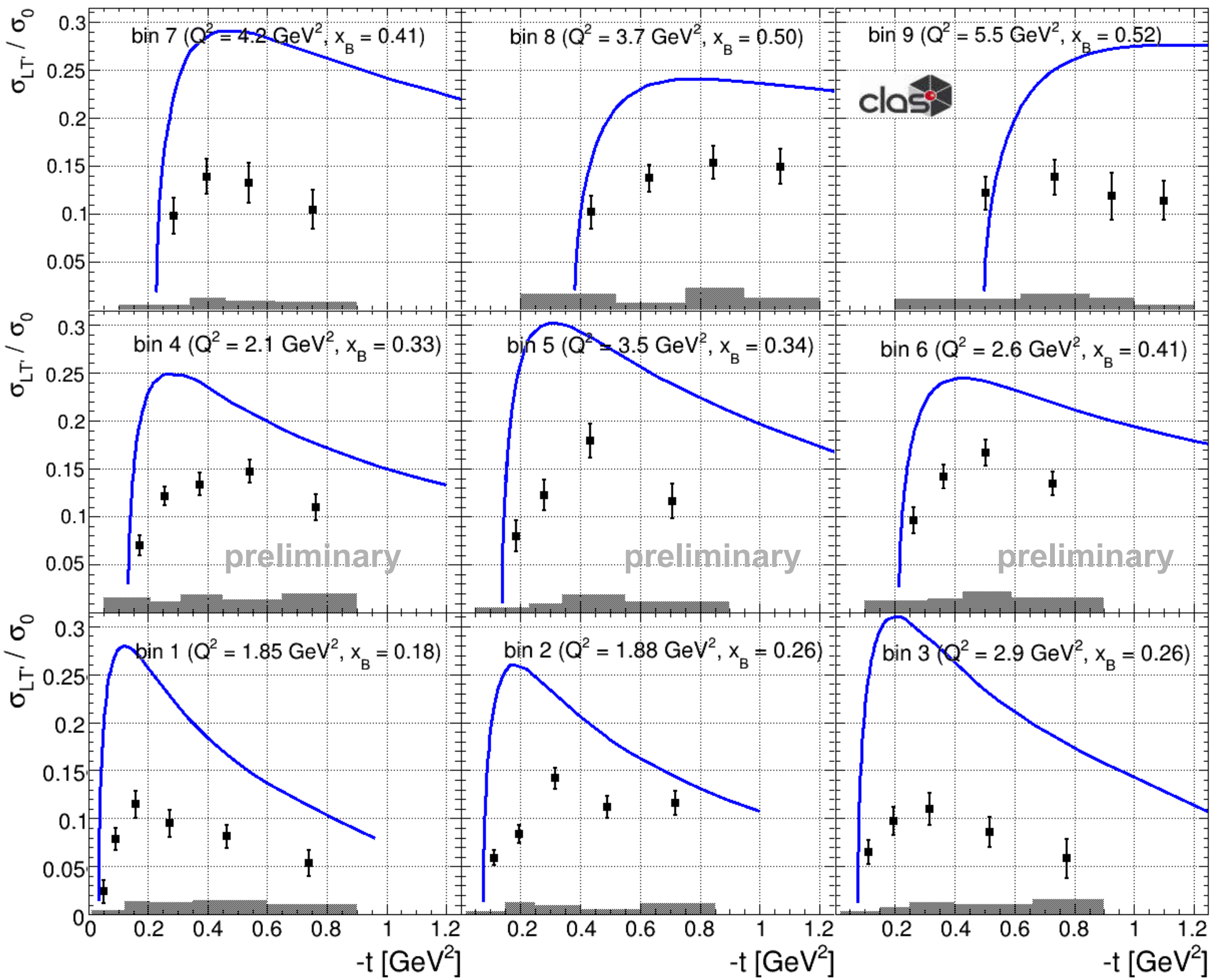
$$ep \rightarrow en\pi^+$$

$$A_{LU}^{\sin\phi} = \frac{\sqrt{2\epsilon(1-\epsilon)}\ \sigma_{LT'}}{\sigma_T + \epsilon\sigma_L}$$

preliminary

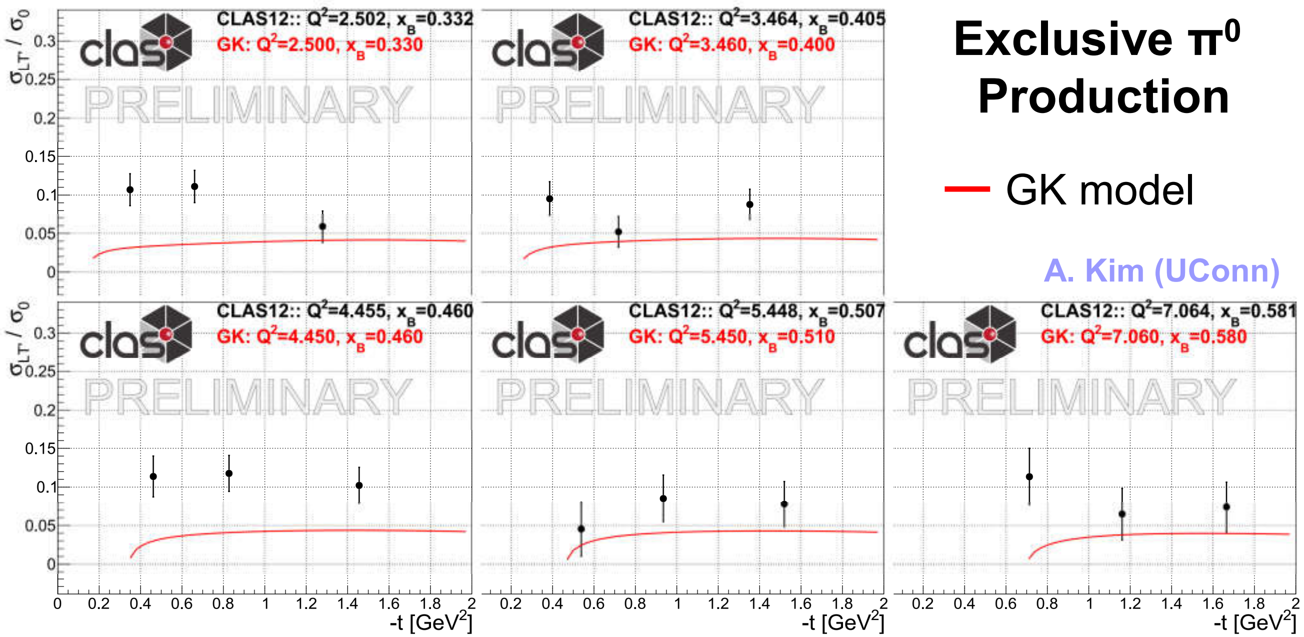



**GK model**




S. Diehl (JLU + UConn)

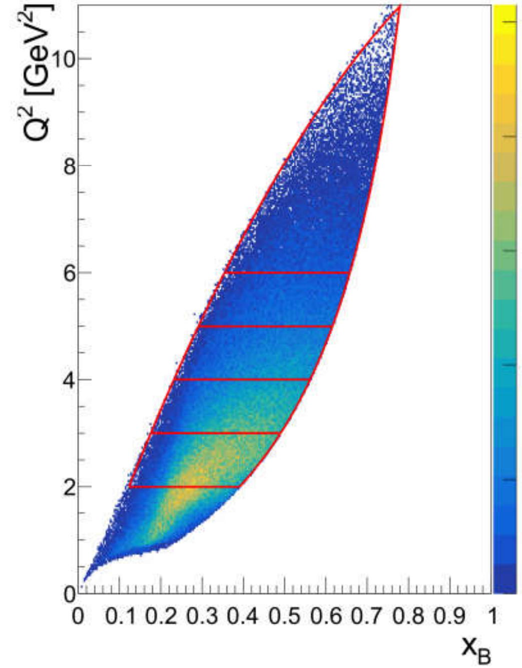
# Deeply Virtual $\pi^0$ and Φ Production with CLAS12



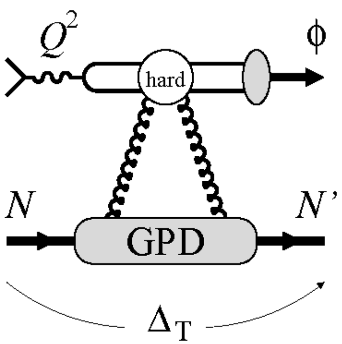

## Exclusive $\pi^0$ Production

— GK model

A. Kim (UConn)

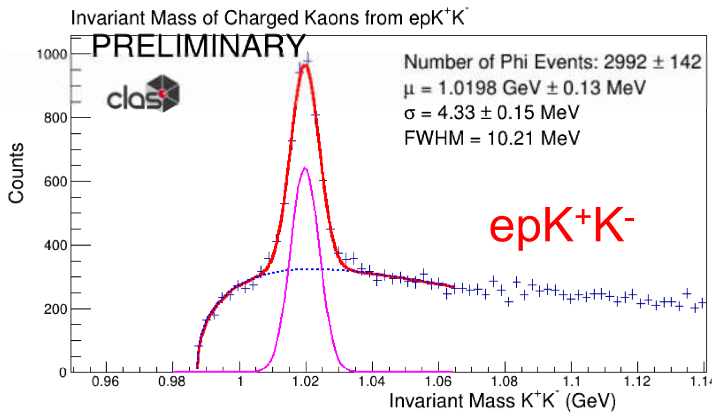



## Exclusive Φ Production




- Exclusive Φ production probes gluon GPDs
- Transverse spatial distribution of gluons

$x < 0.01$ measured at HERA, FNAL
$x > 0.1$ practically unknown




B. Clary (UConn)

# Summary

- TMDs and GPDs provide a unifying framework to study the 3-D quark and gluon structure of the nucleon
- 3-D imaging of nucleons will uncover rich dynamics of QCD
- Exciting time has just started with CLAS12 high precision and high statistics measurements with large kinematic coverages!