Measurement of **quark transverse polarization** at CLAS via π^0 and η exclusive electroproduction

(A. Lung – High impact physics)

Jlab unpolarized π and η experiments measures combinations of generalized form factors GFF

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

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{\left(1-\xi^2\right)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2\,\mathrm{Re}\left[\langle\tilde{H}\rangle\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$$

$$\frac{d\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{\left(1-\xi^2\right)}\frac{\sqrt{-t'}}{8m^2}\mathrm{Re}\left|\langle\bar{E}_T\rangle\langle H\rangle\right|$$

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

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

(Note again: $\bar{E}_T = 2\tilde{H}_T + E_T \Rightarrow \bar{\mathcal{E}}_T = 2\mathcal{H}_T + \mathcal{E}_T$)

H_T and E_T - quark helicity flip

H_T nucleon helicity flip $\qquad$ E_T nucleon helicity non-flip

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

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

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

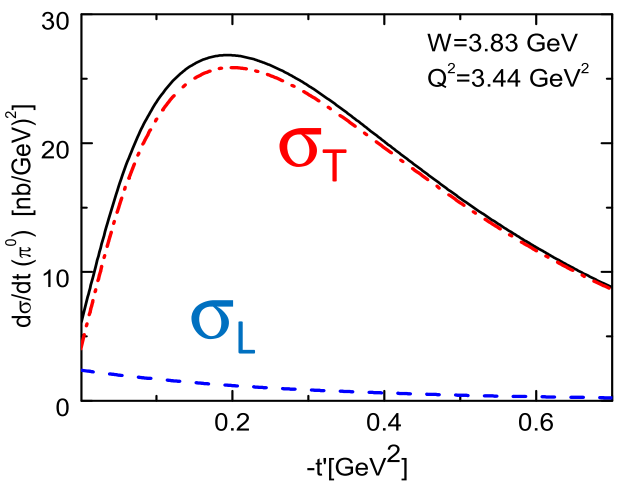
Generalized form factors (GFF)

$$\langle H_T\rangle = \int_{-1}^{1} dx \mathcal{H}_{0\lambda'\mu\lambda} H_T \qquad \langle \bar{E}_T\rangle = \int_{-1}^{1} dx \mathcal{H}_{0\lambda'\mu\lambda} \bar{E}_T$$

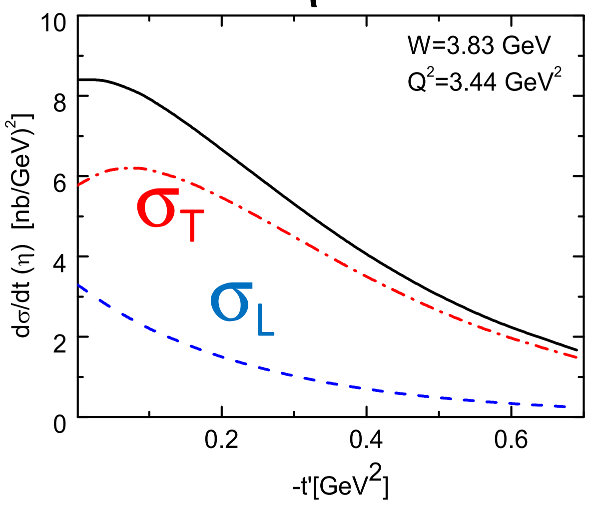
JLab π^0 and η are sensitive to $\bar{E}_T$ and H_T

Goloskokov-Kroll-1106.4897

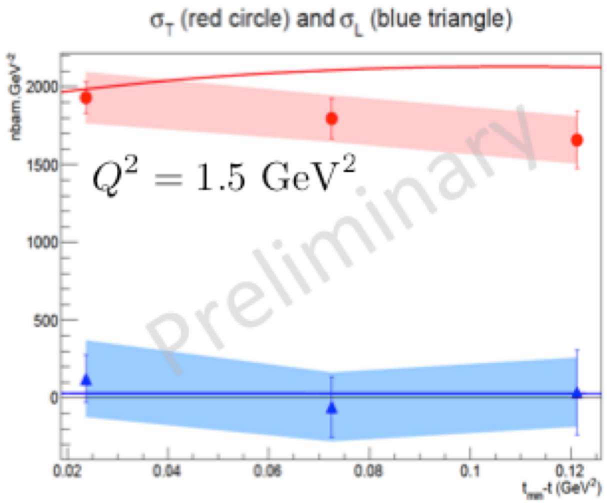
π^0



η



Hall A L/T separation
M. Defurne et al



Decoupling generalized form factors (GFF)

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'} \frac{\mu_\pi^2}{Q^8} \left\{ \left(1-\xi^2\right) \left|\left\langle H_T \right\rangle\right|^2 - \frac{t'}{8m^2} \left|\left\langle E_T \right\rangle\right|^2 \right\}$$

$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'} \frac{\mu_\pi^2}{Q^8} \frac{t'}{16m^2} \left|\left\langle E_T \right\rangle\right|^2$$

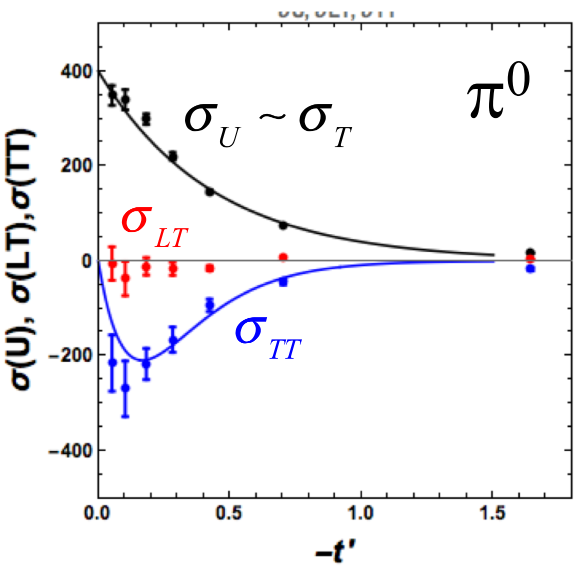
→

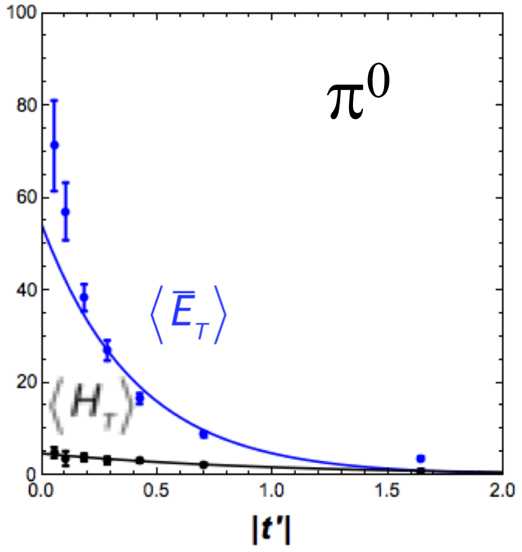
$$\left|\left\langle E_T \right\rangle\right|^2 = \frac{2k'}{4\pi\alpha} \frac{Q^8}{\mu_\pi^2} \frac{16m^2}{t'} \frac{d\sigma_{TT}}{dt}$$

$$\left|\left\langle H_T \right\rangle\right|^2 = \frac{k'}{2\pi\alpha} \frac{Q^8}{\mu_\pi} \frac{1}{\left(1-\xi^2\right)} \left\{ \frac{d\sigma_T}{dt} + \frac{d\sigma_{TT}}{dt} \right\}$$

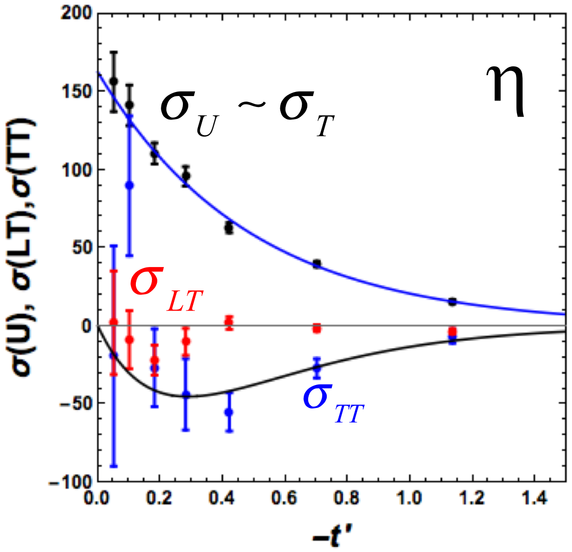
Fit σ_{TT} and $\sigma_U \sim \sigma_T$ $\rightarrow$ $\langle \bar{E}_T \rangle$ and $\langle H_T \rangle$

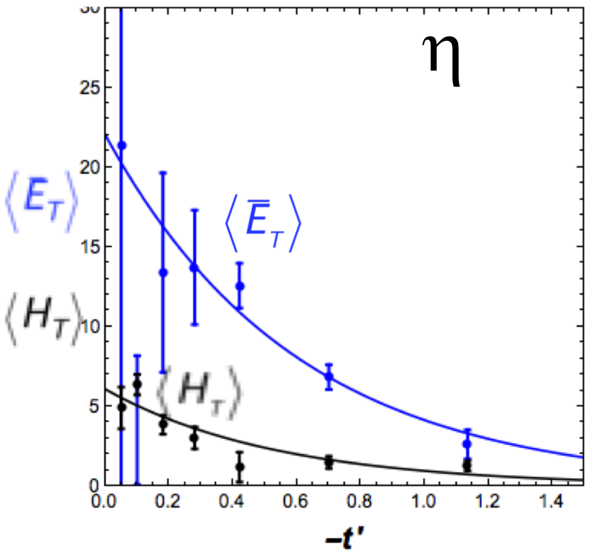
(from VPK)





$$\int_0^{1.0} \frac{\langle \bar{E}_T \rangle}{\langle H_T \rangle} dt' = 6.9$$





$$\int_0^{1.0} \frac{\langle \bar{E}_T \rangle}{\langle H_T \rangle} dt' = 3.9$$

Density of
transversely polarized quarks
in
unpolarized nucleon

(M. Diehl and Ph. Hagler hep-ph/0504175)

GPDs vs impact parameter

Model: Diehl and Hägler, P. Kroll

$$K\left(x,t\right)=k(x)\ e^{f(x)t}$$

(K=GPD, $f(x)$ = profile function, $k(x)$ = normalization)

$$\mathcal{K}\left(x,b\right)=\int\frac{d^2\vec{\Delta}}{(2\pi)^2}\ e^{-i\vec{b}\bullet\vec{\Delta}}K\left(x,t\right)=\frac{1}{4\pi}\frac{k(x)}{f\ (x)}e^{-\frac{b^2}{4f(x)}}$$

Density of transversely polarized quarks vs. impact parameter.

(M. Diehl and Ph. Hagler hep-ph/0504175)

$$q_T(x,\vec{b}) == \frac{1}{2}\Bigg[\mathcal{H} - S^i\varepsilon^{ij}b^j\frac{1}{m}\frac{\partial}{\partial \boldsymbol{b}^2}\mathcal{E} - s^i\varepsilon^{ij}b^j\frac{1}{m}\frac{\partial}{\partial \boldsymbol{b}^2}\bar{\mathcal{E}}_T + s^iS^i\left(\mathcal{H}_T - \frac{1}{4m^2}\Delta_b\tilde{\mathcal{H}}_T\right) + s^i\left(2b^ib^j - b^2\delta^{ij}\right)S^j\frac{1}{m^2}\left(\frac{\partial}{\partial \boldsymbol{b}^2}\right)^2\tilde{\mathcal{H}}_T\Bigg]$$

s^i = quark spin S^i = nucleon spin

Density of transversely polarized quarks in unpolarized nucleon. ($S^i = 0$)

$$q_T(x,\vec{b}) = \frac{1}{2}\left[\mathcal{H} - s^i\varepsilon^{ij}b^j\frac{1}{m}\frac{\partial}{\partial \boldsymbol{b}^2}\bar{\mathcal{E}}_T\right]$$

GPDs vs impact parameter

(GPDs contributing to transverse polarization density for unpolarized nucleon)

$$H(x,t) = h(x)\; e^{f_H(x)t} \quad \Rightarrow \quad \mathcal{H}(x,b) = \frac{1}{4\pi}\frac{h(x)}{f_H(x)}e^{-\frac{b^2}{4 f_H(x)}}$$

$$\bar{E}_T(x,t) = e(x)\; e^{f_e(x)t} \quad \Rightarrow \quad \bar{\mathcal{E}}_T(x,b) = \frac{1}{4\pi}\frac{e(x)}{f_E(x)}\; e^{-\frac{b^2}{4 f_E(x)}}$$

(Note: $\bar{E}_T = 2\tilde{H}_T + E_T \quad \Rightarrow \quad \bar{\mathcal{E}}_T = 2\tilde{\mathcal{H}}_T + \mathcal{E}_T$)

Density of transversely polarized quarks in unpolarized nucleon. $(S^i = 0)$

$$q_T(x,\vec{b}) = \frac{1}{2}\left[\mathcal{H} - s^i \varepsilon^{ij} b^j \frac{1}{m}\frac{\partial}{\partial \boldsymbol{b}^2}\bar{\mathcal{E}}_T\right]$$

Density of quarks polarized in *x* direction:

$$s^i \varepsilon^{ij} b^j \to b^y$$

$$q(x,b) = \frac{1}{2}\left[\frac{1}{4\pi}\frac{h(x)}{f_H(x)} e^{-\frac{b^2}{4 f_H(x)}} + \frac{1}{16\pi m_p}\frac{e(x)}{f_E(x)^2}\, b^y\, e^{-\frac{b^2}{4 f_E(x)}}\right]$$

Extracting GPDs for individual quark flavors.

π^0 and η are members of the same meson multiplet.

Deconvolute π^0 and η to get contributions from quark flavors.

Constituent quark relationships

$$\bar{E}_T^{\pi^0} \approx \frac{1}{\sqrt{2}}(e_u \bar{E}_T^u - e_d \bar{E}_T^d)$$

$$\bar{E}_T^{\eta} \approx \frac{1}{\sqrt{6}}(e_u \bar{E}_T^u + e_d \bar{E}_T^d)$$

$$e_u = 2/3$$

$$e_d = -1/3$$

$\Rightarrow$

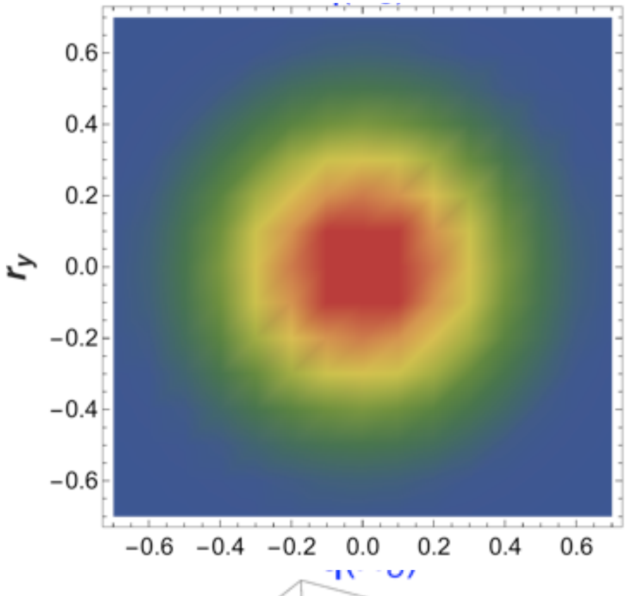
$$\bar{E}_T^u = \frac{3}{2\sqrt{2}}\left(\bar{E}_T^{\pi^0} + \sqrt{3}\bar{E}_T^{\eta}\right)$$

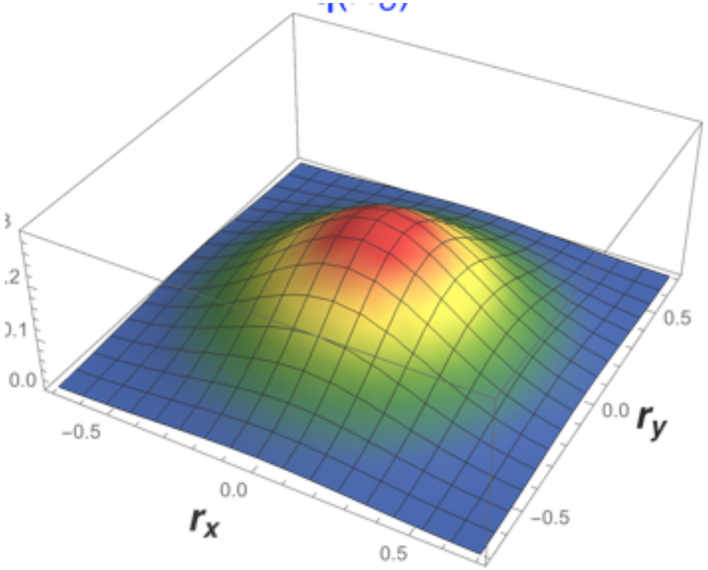
$$\bar{E}_T^d = \frac{3}{\sqrt{2}}\left(\bar{E}_T^{\pi^0} - \sqrt{3}\bar{E}_T^{\eta}\right)$$

$\bar{E}_T^{\pi}$ and $\bar{E}_T^{\eta}$ - Goloskokov and Kroll fit to π^0 and η data.

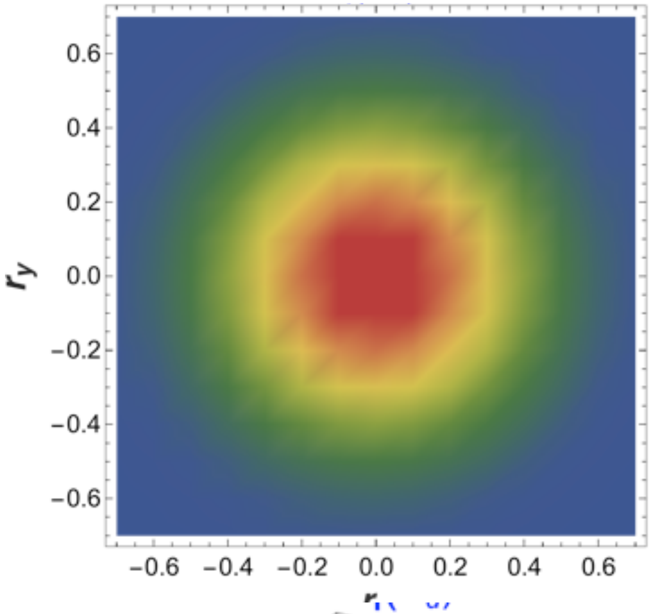
$$q_H(x,\vec{b}) = \frac{1}{2}\mathcal{H}$$

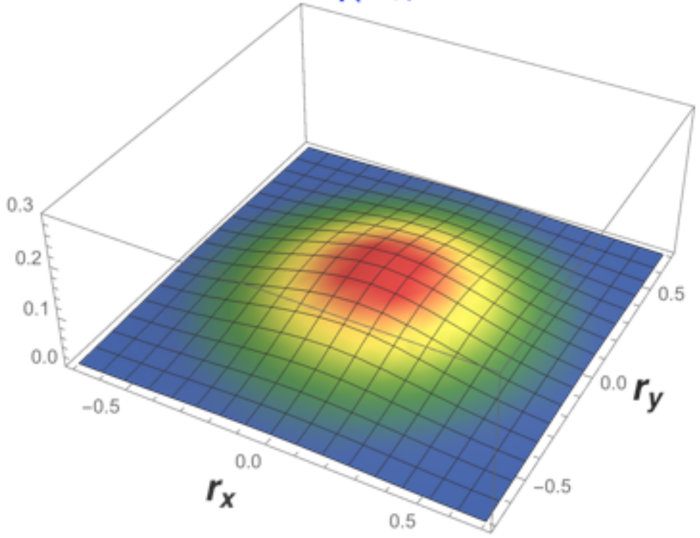
$q(\mathcal{H}_u)$





$q(\mathcal{H}_d)$



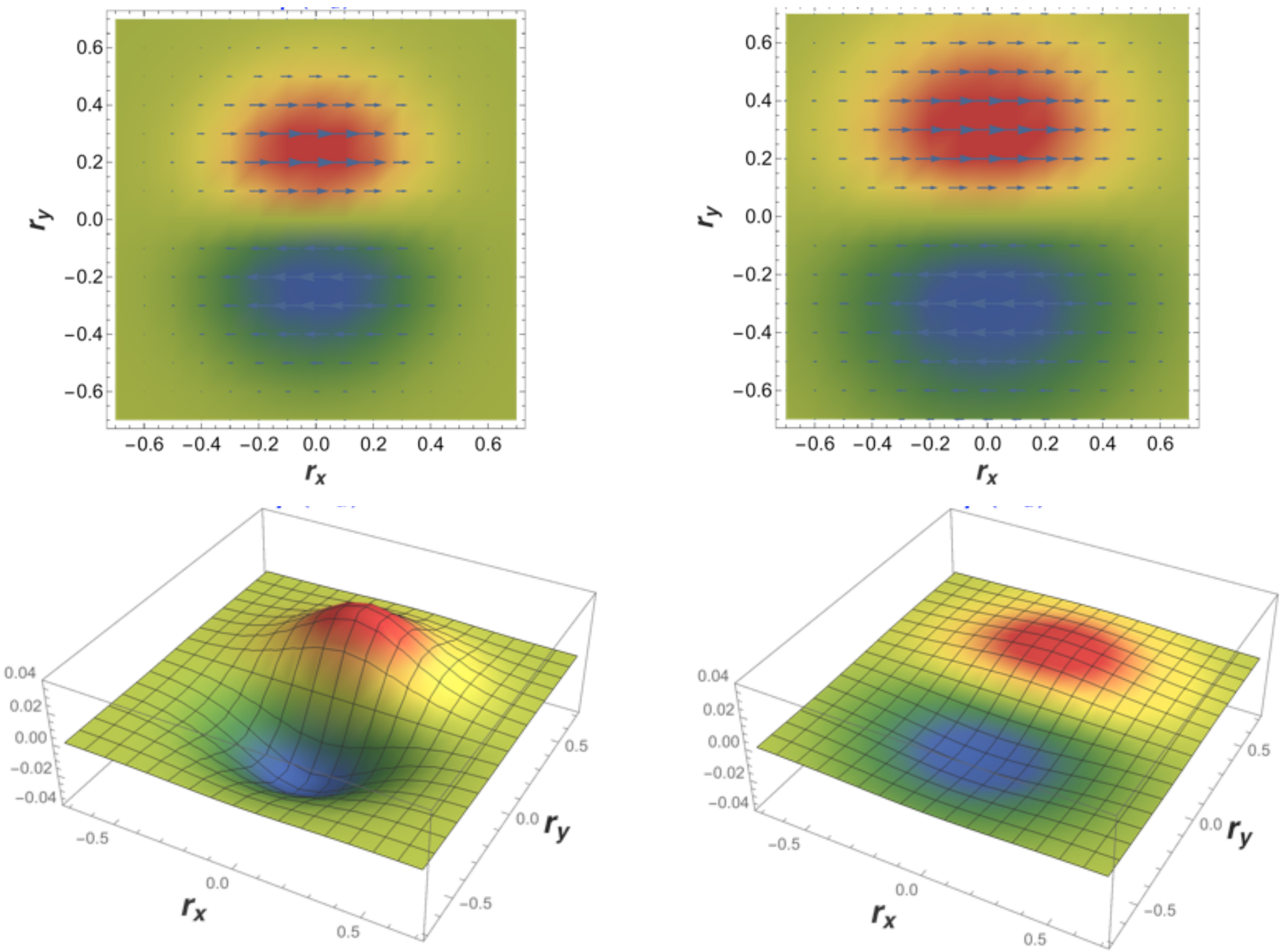


$x = 0.2$

Prameters from DVCS
(Diehl & Hagler)

$$q_T(x, b^x) \equiv \frac{1}{2} b^y \frac{1}{m} \frac{\partial}{\partial \boldsymbol{b}^2} \bar{\mathcal{E}}_T$$

$q\left(\bar{\mathcal{E}}_{T\,u}\right)$ $q\left(\bar{\mathcal{E}}_{T\,d}\right)$

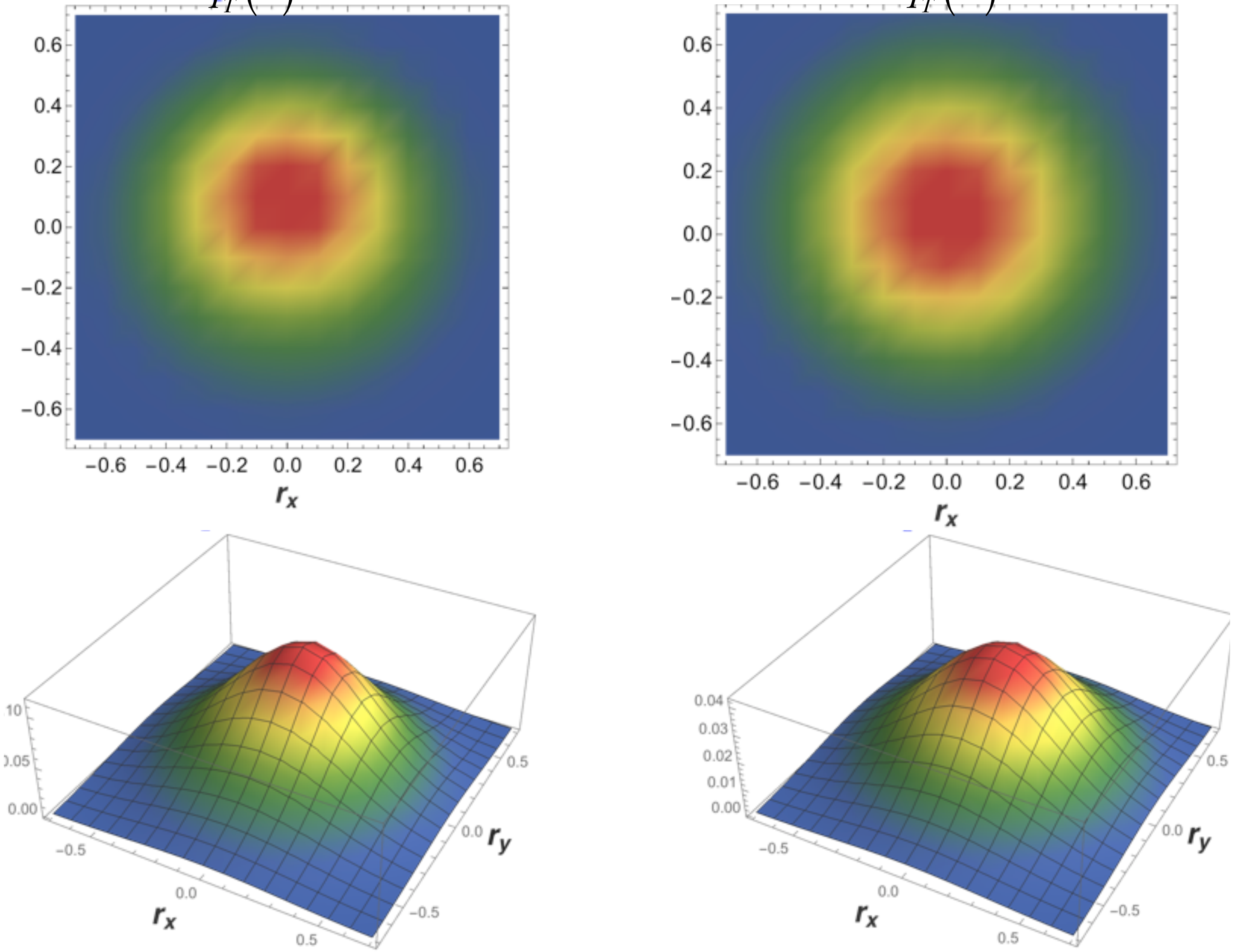


$x = 0.2$

Parameters π^0, η Goloskokov & Kroll from Hall B data

$$q_T = q(\mathcal{H}) + q(\bar{\mathcal{E}}_T)$$

$q_T(u)$ $q_T(d)$



$x = 0.2$

Density of transversely polarized quarks in unpolarized nucleon.

$$q_T(x,\vec{b}) = \frac{1}{2}\left[\mathcal{H} - s^i \varepsilon^{ij} b^j \frac{1}{m} \frac{\partial}{\partial \boldsymbol{b}^2} \bar{\mathcal{E}}_T \right]$$

Density of quarks polarized in *x*-*y* plane:

$$s^i \varepsilon^{ij} b^j \rightarrow b^x \hat{x} - b^y \hat{y}$$

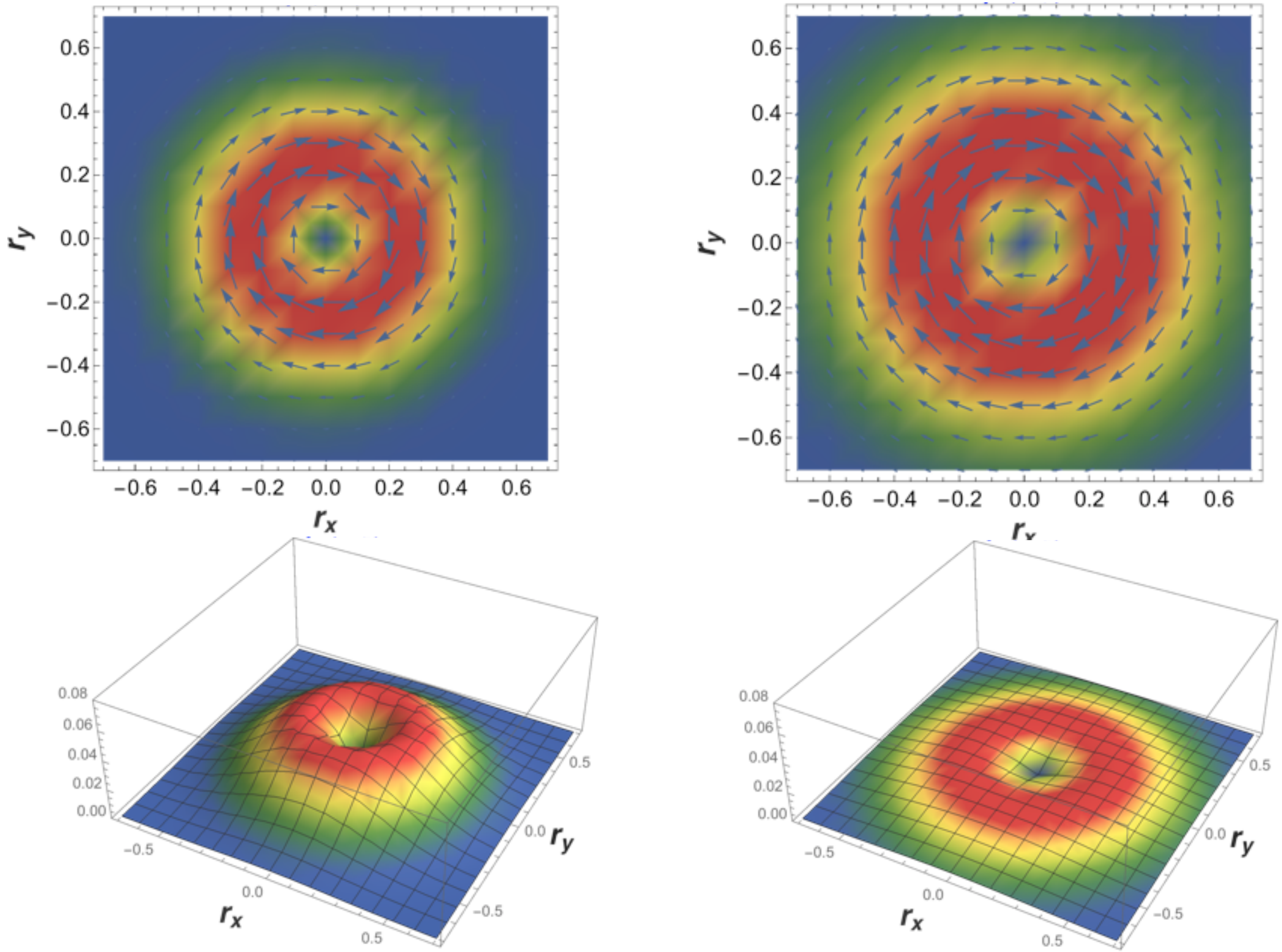
$$q\left(x,\vec{b}\right) = \frac{1}{2}\left[\frac{1}{4\pi} \frac{h(x)}{f_H(x)} e^{-\frac{b^2}{4 f_H(x)}} + \frac{1}{16\pi m_p} \frac{e(x)}{f_E(x)^2} \left(b^x \hat{x} - b^y \hat{y}\right) e^{-\frac{b^2}{4 f_E(x)}} \right]$$

$$b = \sqrt{b_x^2 + b_y^2}$$

$$q\left(x,b\right) = \frac{1}{2}\left[\frac{1}{4\pi} \frac{h(x)}{f_H(x)} e^{-\frac{b^2}{4 f_H(x)}} + \frac{1}{16\pi m_p} \frac{e(x)}{f_E(x)^2} \sqrt{b_y^2 + b_x^2}\; e^{-\frac{b^2}{4 f_E(x)}} \right]$$

$$q_T(x,\vec{b}) \equiv \frac{1}{2}\,(b^x\hat{x} - b^y\hat{y})\;\frac{1}{m}\frac{\partial}{\partial \boldsymbol{b}^2}\bar{\mathcal{E}}_T$$

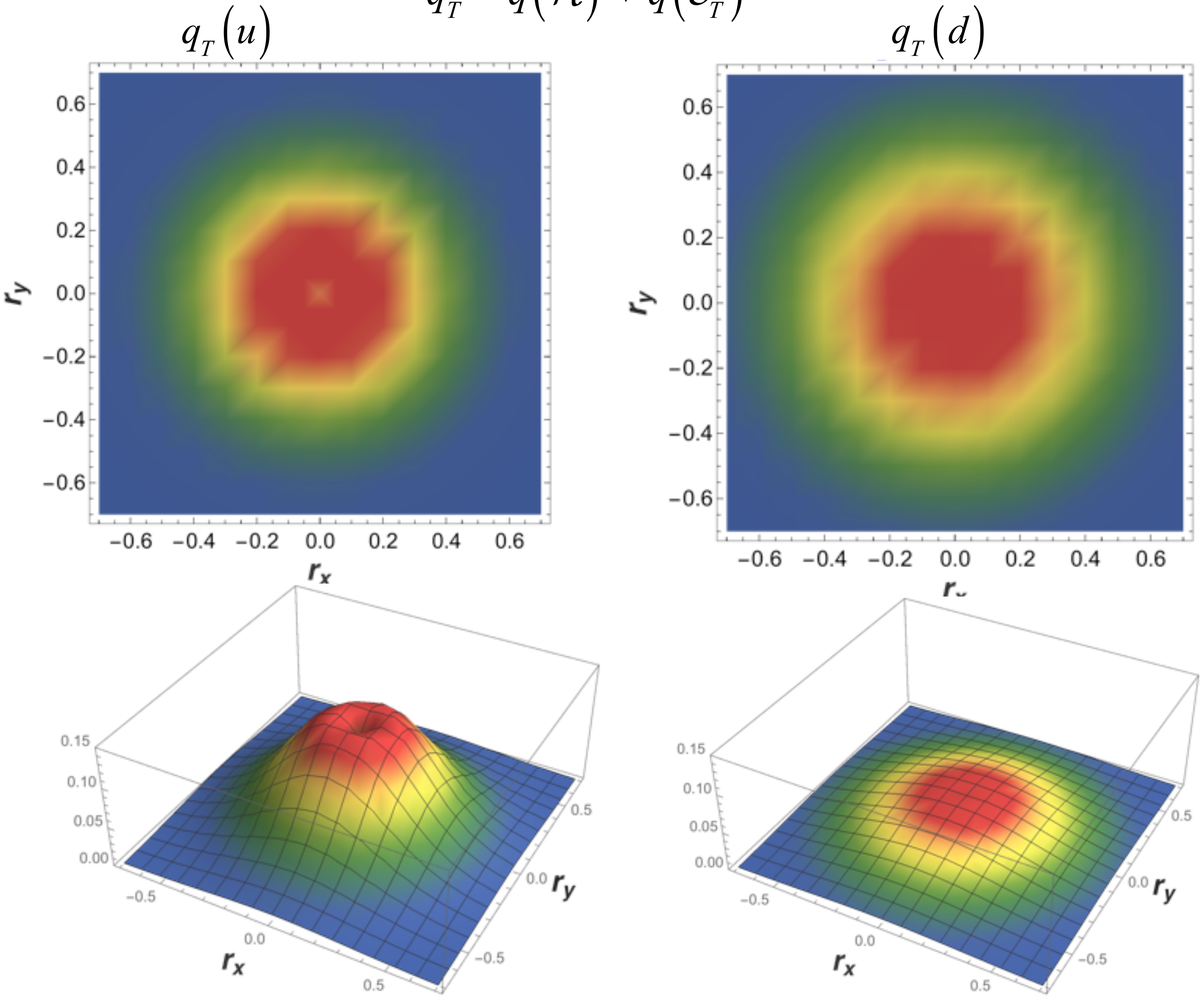
$q\left(\bar{\mathcal{E}}_{T\,u}\right)$ $q\left(\bar{\mathcal{E}}_{T\,d}\right)$



$x = 0.2$

Parameters π^0, η Goloskokov & Kroll from Hall B data

$$q_T = q(\mathcal{H}) + q(\bar{\mathcal{E}}_T)$$



$x = 0.2$

Extracting GFFs for individual quark flavors.

Assume constituent quark relationships

(See VK)

$$\bar{E}_T^u = \frac{3}{2\sqrt{2}}\left(\bar{E}_T^{\pi^0} + \sqrt{3}\bar{E}_T^{\eta}\right)$$

$$\bar{E}_T^d = \frac{3}{\sqrt{2}}\left(\bar{E}_T^{\pi^0} - \sqrt{3}\bar{E}_T^{\eta}\right)$$

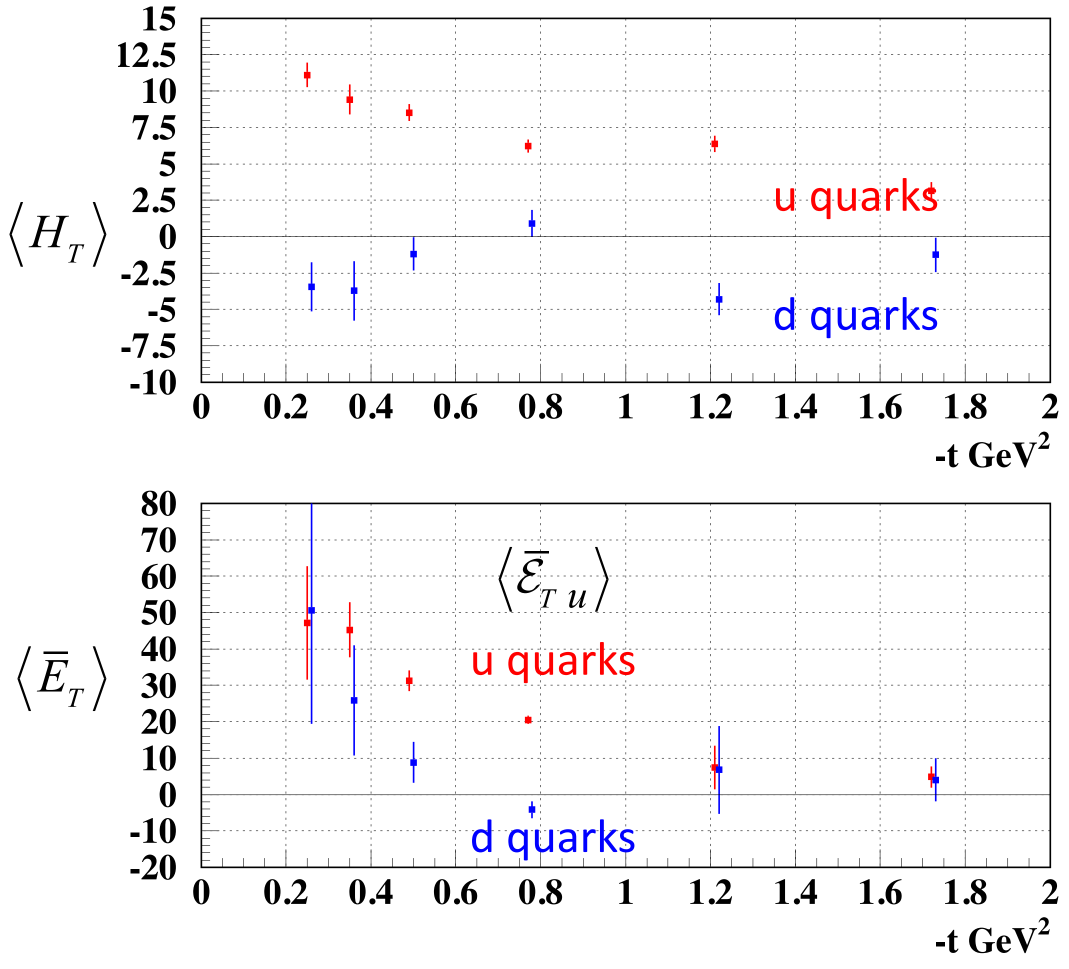
Assumption →

$$\left\langle \bar{E}_T^u \right\rangle = \frac{3}{2\sqrt{2}}\left(\left\langle \bar{E}_T^{\pi^0} \right\rangle + \sqrt{3}\left\langle \bar{E}_T^{\eta} \right\rangle\right)$$

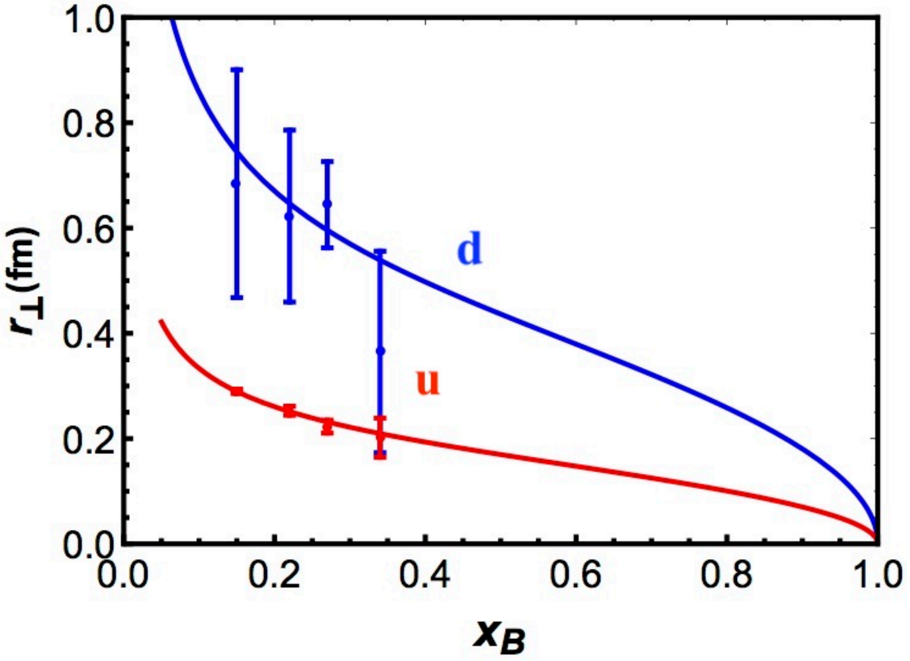
$$\left\langle \bar{E}_T^d \right\rangle = \frac{3}{\sqrt{2}}\left(\left\langle \bar{E}_T^{\pi^0} \right\rangle - \sqrt{3}\left\langle \bar{E}_T^{\eta} \right\rangle\right)$$

VPK. u-d separation

Q^2=1.8 GeV^2, x_B=0.22



PS fit



Scale factor >2

Note: each x_b - continuum distribution of x

Assume $\frac{r_d}{r_u}$ of $\langle \bar{E}_T \rangle \rightarrow \frac{r_d}{r_u}$ of $\bar{E}_T$

Recalculate number density $q(\bar{E}_T)$

down quarks: $$q_d \propto \frac{b}{A_d f_d(x)} e^{-\frac{b^2}{4 A_d^2 f_d(x)}} \qquad \langle b_d \rangle = \frac{\int b\, q_d(b)\, db}{\int q_d(b)\, db}$$

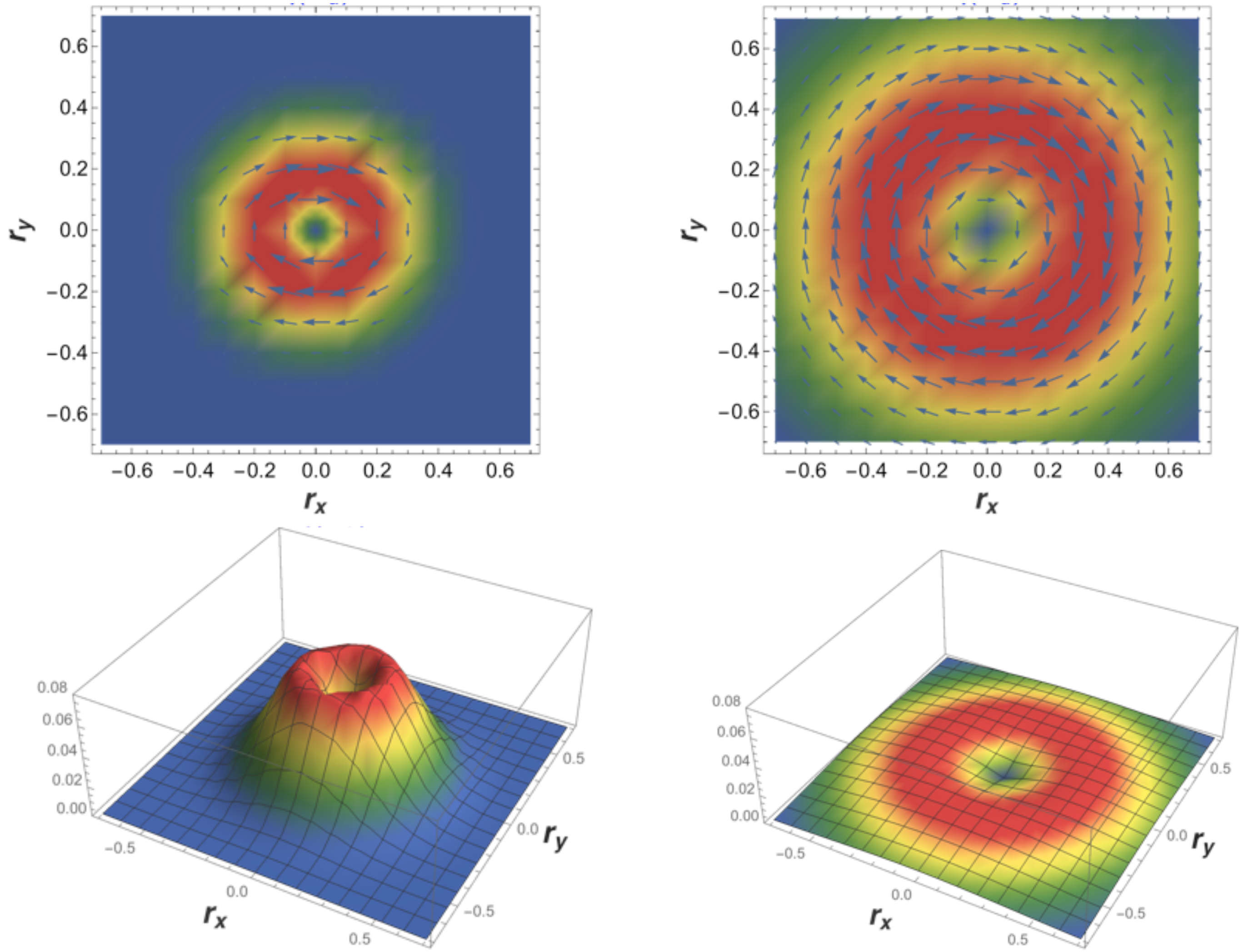
up quarks: $$q_u \propto \frac{b}{A_u f_n(x)} e^{-\frac{b^2}{4 A_u^2 f_u(x)}} \qquad \langle b_u \rangle = \frac{\int b\, q_u(b)\, db}{\int q_u(b)\, db}$$

A_d and A_u adjusted so that $A_d / A_u = 2$

q_d and q_u renormalized such that N_d and N_u do not change.

$$q_T(x,\vec{b}) \equiv \frac{1}{2}\,(b^x\hat{x} - b^y\hat{y})\,\frac{1}{m}\frac{\partial}{\partial \boldsymbol{b}^2}\bar{\mathcal{E}}_T$$

$q\left(\bar{\mathcal{E}}_{T\,u}\right)$ $\qquad$ $q\left(\bar{\mathcal{E}}_{T\,d}\right)$

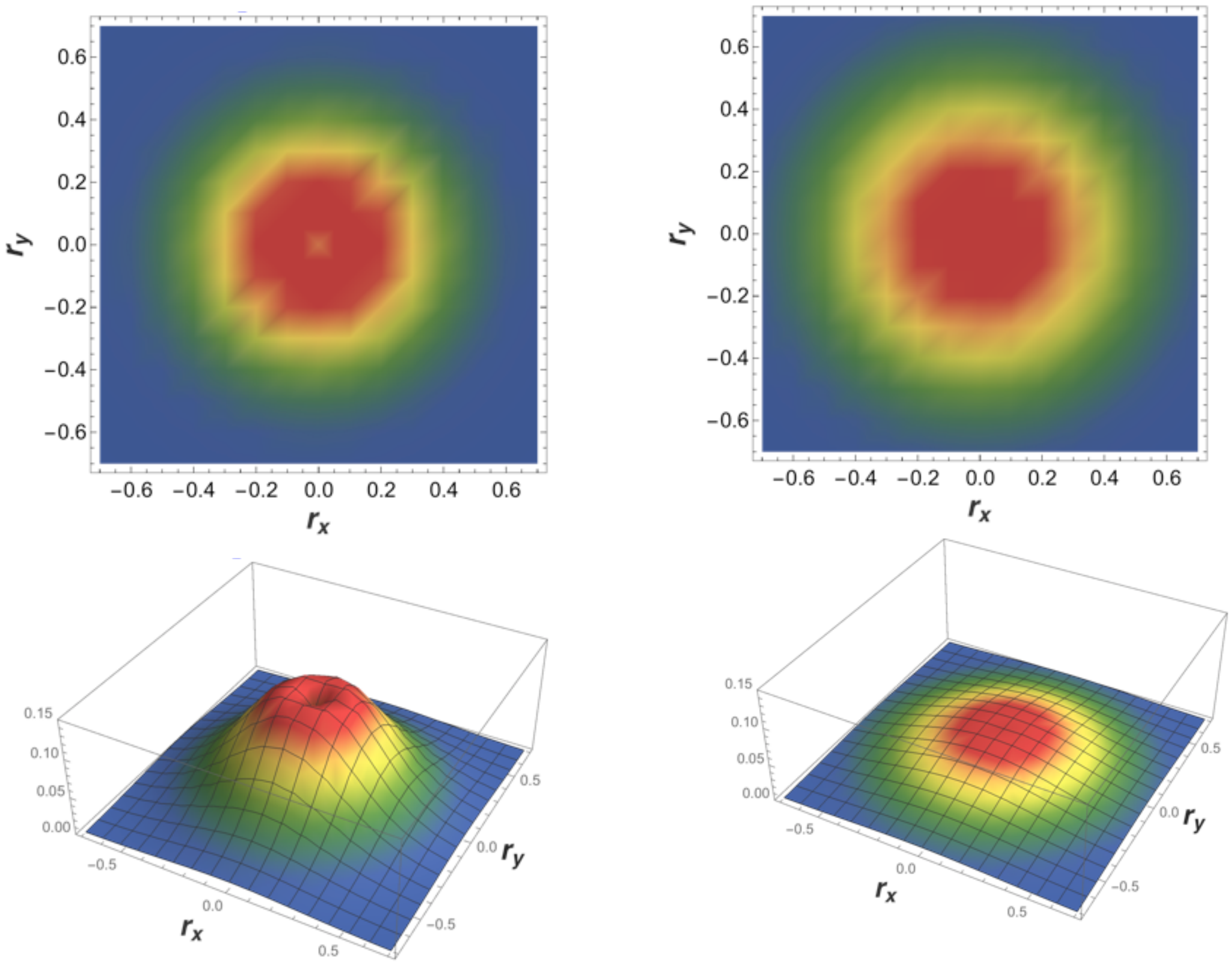


$x = 0.2$

$\langle b_d \rangle = 2\langle b_u \rangle$

$$q_T = q(\mathcal{H}) + q(\bar{\mathcal{E}}_T)$$

$q_T(u)$ $q_T(d)$



$x = 0.2$

Conclusion:

π^0 and η meson production is a unique tool for obtaining distributions of transversely polarized quarks in a nucleon.

They are a significant component of the JLab program, along with the suite of exclusive reactions, such as DVMP, and ϕ meson production, to map the quark/gluon distributions in terms of the GPD formalism, in the nucleon.