Transverse (Spin) Structure of Hadrons

Matthias Burkardt

New Mexico State University

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Outline

- Deeply virtual Compton scattering (DVCS)

$\hookrightarrow$ Generalized parton distributions (GPDs)

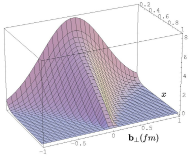
$\hookrightarrow$ 'transverse imaging'

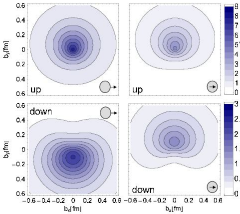
- Chromodynamik lensing and $\perp$ single-spin asymmetries (SSA)

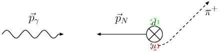
$$\left.\begin{array}{c}\text{transverse distortion of PDFs}\\ +\text{ final state interactions}\end{array}\right\} \Rightarrow$$

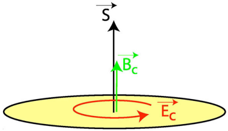
$\hookrightarrow$ SSA in $\quad \gamma N \longrightarrow \pi + X$

- quark-gluon correlations $\rightarrow \perp$ force on q in DIS
- Summary









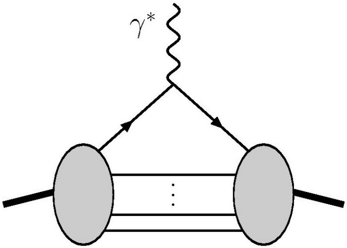
3 D imaging — join the experience!

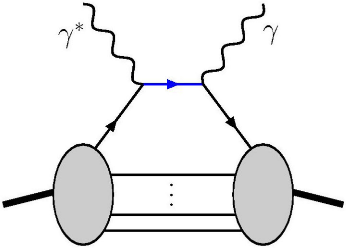
- virtual Compton scattering: $\gamma^* p \longrightarrow \gamma p$ (actually: $e^- p \longrightarrow e^- \gamma p$)
- 'deeply': $-q_\gamma^2 \gg M_p^2, |t| \longrightarrow$ Compton amplitude dominated by (coherent superposition of) Compton scattering off single quarks

$\hookrightarrow$ only difference between form factor (a) and DVCS amplitude (b) is replacement of photon vertex by two photon vertices connected by quark (energy denominator depends on quark momentum fraction x)

$\hookrightarrow$ DVCS amplitude provides access to momentum-decomposition of form factor = Generalized Parton Distribution (GPDs).

$$\int dx H_q(x,\xi,t) = F_1^q(t) \qquad \int dx E_q(x,\xi,t) = F_2^q(t)$$





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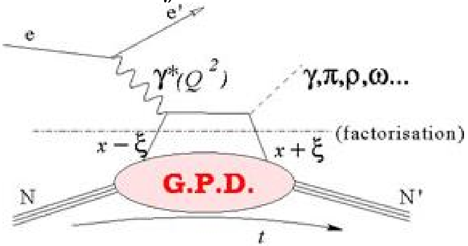


future experiments

JLab@12GeV, Compass II, EIC, Panda/FAIR

- form factors: $\stackrel{FT}{\longleftrightarrow} \rho(\vec{r})$
- $GPDs(x,\vec{\Delta})$: form factor for quarks with momentum fraction x

$\hookrightarrow$ suitable FT of $GPDs$ should provide spatial distribution of quarks with momentum fraction x

- careful: cannot measure longitudinal momentum (x) and longitudinal position simultaneously (Heisenberg)

$\hookrightarrow$ consider purely transverse momentum transfer

Impact Parameter Dependent Quark Distributions

$$q(x,\mathbf{b}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} H(x,\xi=0,-\mathbf{\Delta}_\perp^2) e^{-i\mathbf{b}_\perp\cdot\mathbf{\Delta}_\perp}$$

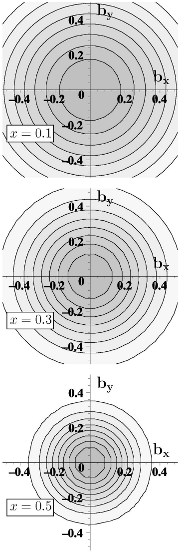
$q(x,\mathbf{b}_\perp)$ = parton distribution as a function of the separation $\mathbf{b}_\perp$ from the transverse center of momentum $\mathbf{R}_\perp \equiv \sum_{i\in q,g} \mathbf{r}_{\perp,i} x_i$
MB, Phys. Rev. D62, 071503 (2000)

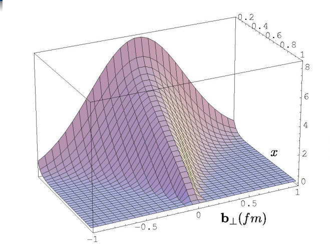
- No relativistic corrections (Galilean subgroup!)

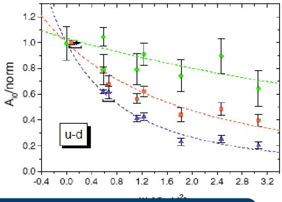
$\hookrightarrow$ corollary: interpretation of 2d-FT of $F_1(Q^2)$ as charge density in transverse plane also free of relativistic corrections

- probabilistic interpretation

$q(x, \mathbf{b}_\perp)$ for unpol. p





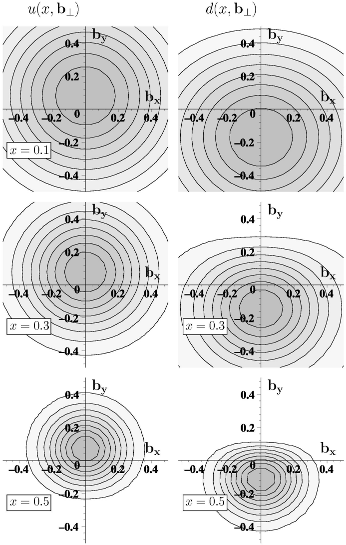


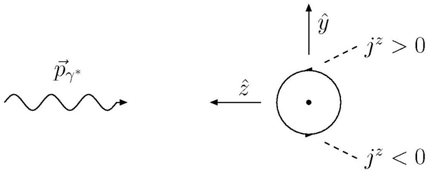
unpolarized proton

- $q(x, \mathbf{b}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} H(x, 0, -\mathbf{\Delta}_\perp^2) e^{-i\mathbf{b}_\perp \cdot \mathbf{\Delta}_\perp}$
- x = momentum fraction of the quark
- $\vec{b} = \perp$ distance of quark from $\perp$ center of momentum
- small x: large 'meson cloud'
- larger x: compact 'valence core'
- $x \to 1$: active quark becomes center of momentum

$\hookrightarrow$ $\vec{b}_\perp \to 0$ (narrow distribution) for $x \to 1$

Impact parameter dependent quark distributions





proton polarized in $+\hat{x}$ direction

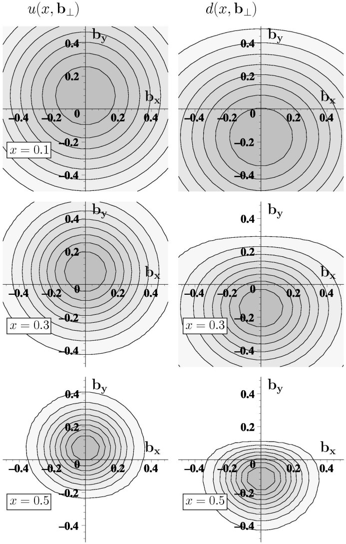
no axial symmetry!

$$q(x, \mathbf{b}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} H_q(x, 0, -\Delta_\perp^2) e^{-i\mathbf{b}_\perp \cdot \Delta_\perp}$$

$$- \frac{1}{2M} \frac{\partial}{\partial b_y} \int \frac{d^2\Delta_\perp}{(2\pi)^2} E_q(x, 0, -\Delta_\perp^2) e^{-i\mathbf{b}_\perp \cdot \Delta_\perp}$$

Physics: relevant density in leading twist DIS is $j^+ \equiv j^0 + j^3$ and left-right asymmetry from j^3

MB, Int. J. Mod. Phys. **A18**, 173 (2002)



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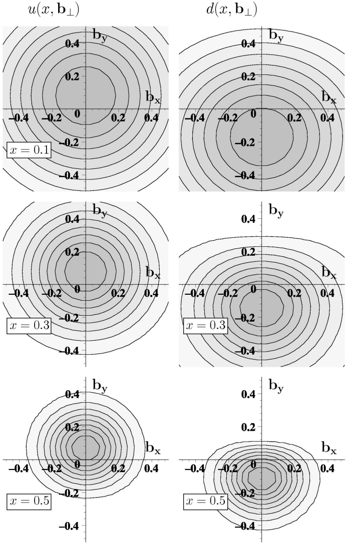
sign & magnitude of the average shift

model-independently related to p/n anomalous magnetic moments:

$$\langle b_y^q \rangle \equiv \int dx \int d^2 b_\perp q(x, \mathbf{b}_\perp) b_y$$

$$= \frac{1}{2M} \int dx E_q(x, 0, 0) = \frac{\kappa_q}{2M}$$



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$$\kappa^p = 1.913 = \frac{2}{3}\kappa_u^p - \frac{1}{3}\kappa_d^p + ...$$

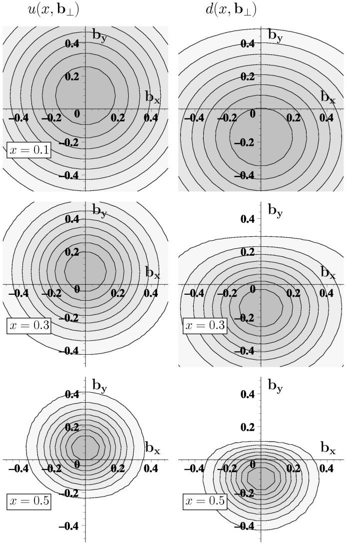
- u-quarks: $\kappa_u^p = 2\kappa_p + \kappa_n = 1.673$

$\hookrightarrow$ shift in $+\hat{y}$ direction

- d-quarks: $\kappa_d^p = 2\kappa_n + \kappa_p = -2.033$

$\hookrightarrow$ shift in $-\hat{y}$ direction

- $\langle b_y^q \rangle = \mathcal{O}(\pm 0.2 fm)$!!!!



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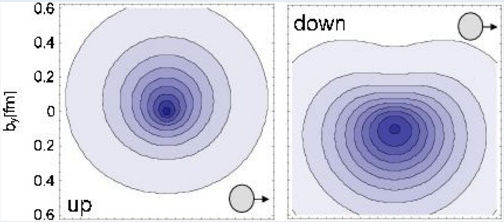
lattice QCD (QCDSF): lowest moment



transverse images $\leftrightarrow$ Ji relation for quark angular momentum:

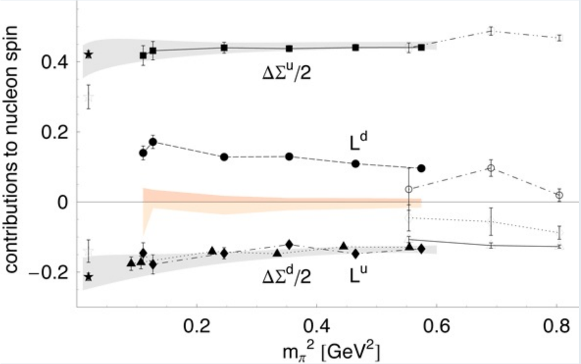
- $J_q^x = m_N \int dx\, x r^y q(x,\mathbf{r}_\perp)$ with $b^y = r^y - \frac{1}{2m_N}$, where $q(x,\mathbf{r}_\perp)$ is distribution relative to CoM of whole nucleon
- recall: $q(x,\mathbf{b}_\perp)$ for nucleon polarized in $+\hat{x}$ direction

$$\begin{aligned} q(x,\mathbf{b}_\perp) &= \int \frac{d^2\Delta_\perp}{(2\pi)^2} H_q(x,0,-\Delta_\perp^2) e^{-i\mathbf{b}_\perp\cdot\Delta_\perp} \\ &\quad - \frac{1}{2M_N}\frac{\partial}{\partial b_y}\int \frac{d^2\Delta_\perp}{(2\pi)^2} E_q(x,0,-\Delta_\perp^2) e^{-i\mathbf{b}_\perp\cdot\Delta_\perp} \end{aligned}$$

$$\begin{aligned} \Rightarrow J_q^x &= M_N \int dx\, x r^y q(x,\mathbf{r}_\perp) = \int dx\, x \left(m_N b^y + \frac{1}{2}\right) q(x,\mathbf{r}_\perp) \\ &= \frac{1}{2}\int dx\, x\, [H(x,0,0) + E(x,0,0)] \end{aligned}$$

- X.Ji(1996): rotational invariance $\Rightarrow$ apply to all components of $\vec{J}_q$
- partonic interpretation exists only for $\perp$ components!

lattice: QCDSF



- no disconnected quark loops
- chiral extrapolation

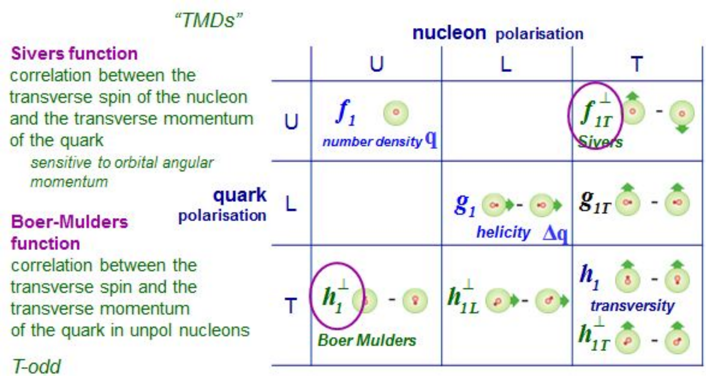
$$J^q = \frac{1}{2}\int dx\, x\,[H(x,0,0) + E(x,0,0)] \qquad L^q = J^q - \frac{1}{2}\Delta\Sigma^q$$

TMDs

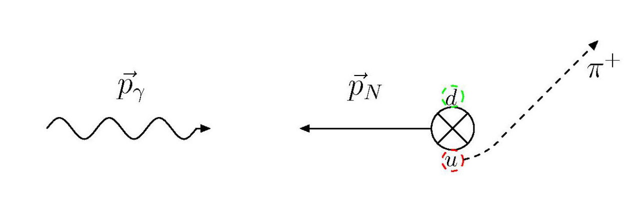
- Transverse Momentum Dependent Parton Distributions
- 8 structures possible at leading twist (only 3 for PDFs)
- $f_{1T}^{\perp}$ and $h_1^{\perp}$ require both orbital angular momentum and final state interaction
- can be measured in semi-inclusive deep-inelastic scattering (SIDIS) & Drell-Yan (DY) $q\bar{q} \rightarrow \mu^+\mu^-$

experiments

JLab@6GeV & 12GeV, HERMES, COMPASS I & II, RHIC, EIC, FAIR/PANDA



Sivers $f_{1T}^{\perp}$ in semi-inclusive deep-inelastic scattering (SIDIS) $\gamma p \to \pi X$



- u, d distributions in $\perp$ polarized proton have left-right asymmetry in $\perp$ position space (T-even!); sign 'determined' by κ_u & κ_d
- attractive FSI deflects active quark towards the CoM

$\hookrightarrow$ FSI translates position space distortion (before the quark is knocked out) in $+\hat{y}$-direction into momentum asymmetry that favors $-\hat{y}$ direction $\to$ 'chromodynamic lensing'

$\Rightarrow$ $\kappa_p\,,\kappa_n \quad \longleftrightarrow \quad$ sign of SSA!!!!!!!! MB, PRD 69, 074032 (2004)

- confirmed by Hermes (and recent Compass) p data; consistent with vanishing isoscalar Sivers (Compass) $\longrightarrow$ G. Schnell compare FSI for 'red' q that is being knocked out of nucleon with ISI for 'anti-red' $\bar{q}$ that is about to annihilate with a 'red' target q

FSI in SIDIS

- knocked-out q 'red'
- ↪ spectators 'anti-red'
- ↪ interaction between knocked-out quark and spectators attractive

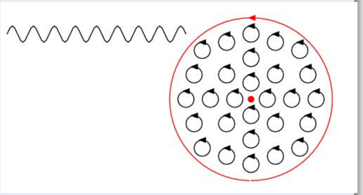
ISI in DY

- incoming $\bar{q}$ 'anti-red'
- ↪ struck target q 'red'
- ↪ spectators also 'anti-red'
- ↪ interaction between incoming $\bar{q}$ and spectators repulsive

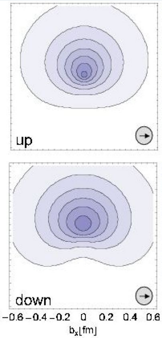
test of $f_{1T}^{\perp}(x, \mathbf{k}_\perp)_{DY} = -f_{1T}^{\perp}(x, \mathbf{k}_\perp)_{SIDIS}$ and $h_1^{\perp}(x, \mathbf{k}_\perp)_{DY} = -h_1^{\perp}(x, \mathbf{k}_\perp)_{SIDIS}$
critical test of TMD factorization approach

Sign of Boer-Mulders Function

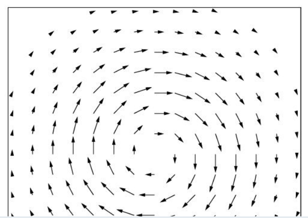
q with polarization $\odot$



lattice calculation (QCDSF)



unpolarized target



- transversity distribution in unpol. target described by chirally odd GPD $\bar{E}_T$ (M.Diehl & P.Haegler '05)
- $\bar{E}_T > 0$ for u & d (QCDSF)
- connection $h_1^\perp(x, \mathbf{k}_\perp) \leftrightarrow \bar{E}_T$ similar to $f_{1T}^\perp(x, \mathbf{k}_\perp) \leftrightarrow E$ (MB '05)

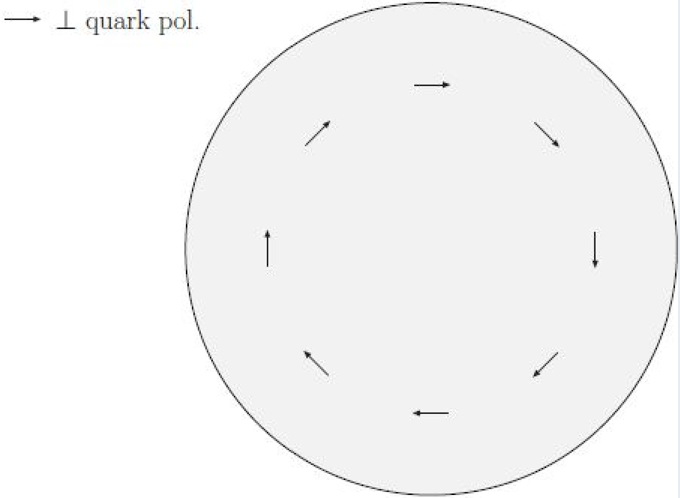
$\hookrightarrow$ $h_1^\perp(x, \mathbf{k}_\perp) < 0$ for u/p, d/p, u/π, $\bar{d}/\pi$

- $h_1^\perp{}_{SIDIS} = -h_1^\perp{}_{DY}$

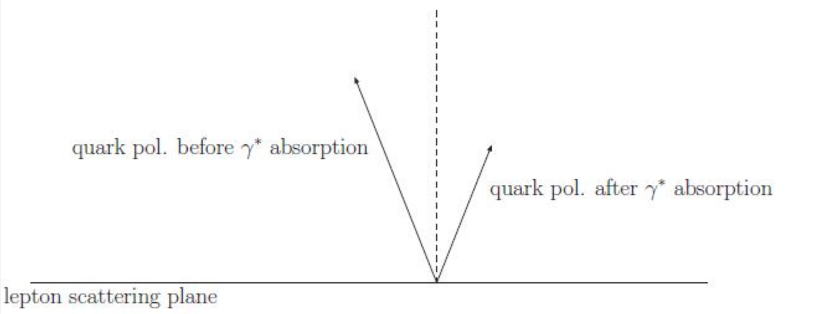
experiments (no polarization needed!):

Hermes, Compass, RHIC, JLab@12GeV, FAIR/Panda, EIC

Primordial Quark Transversity Distribution



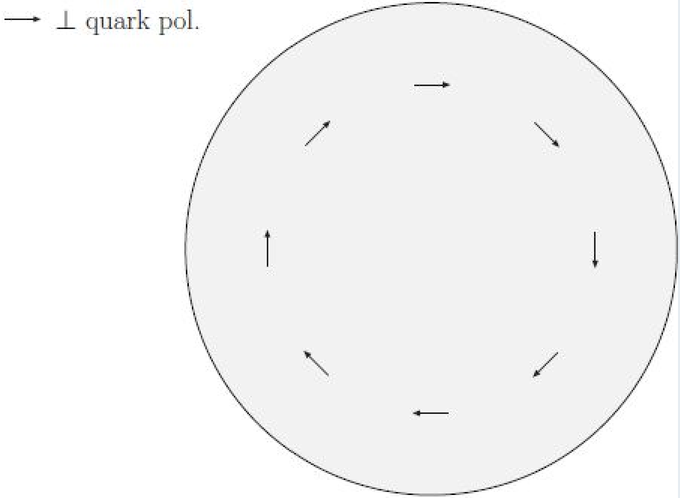
Flip of Quark Transverse Spin Component



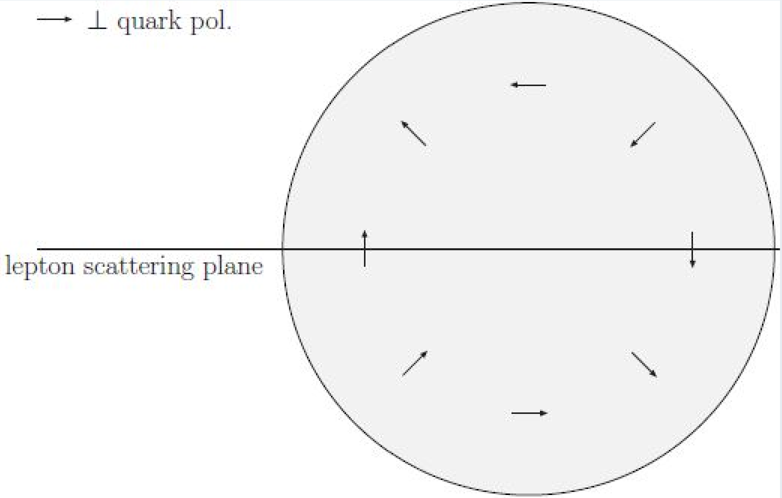
when $\perp$ pol. quark absorbs γ^*, $\perp$ polarization

- gets reduced in size
- tilted symmetrically w.r.t. normal of lepton scattering plane

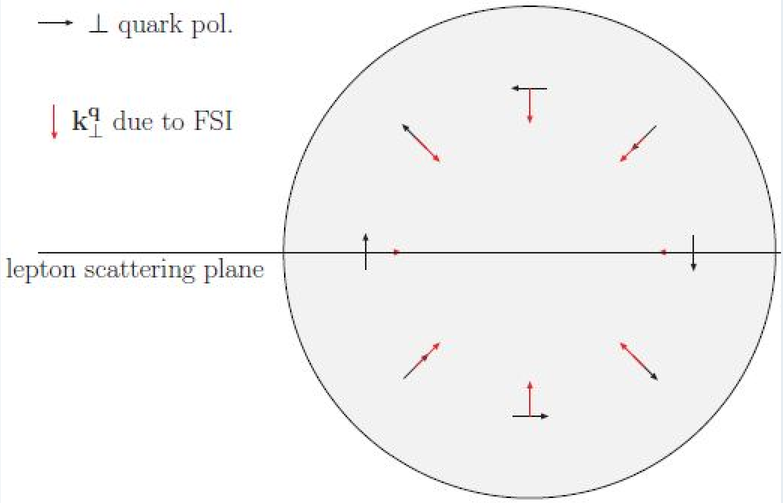
Primordial Quark Transversity Distribution



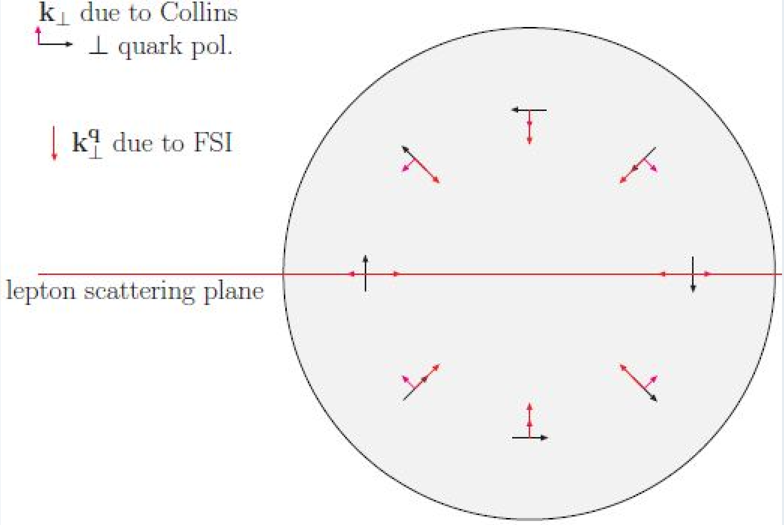
Quark Transversity Distribution after γ^* Absorption



⊥ momentum (of q) due to FSI

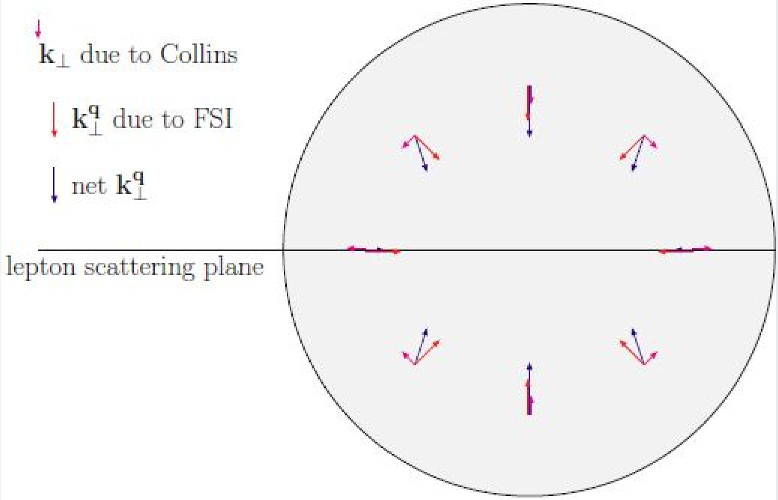


additional ⊥ momentum (of π) due to Collins effect



Collins: favored π momentum preferentially to left (quark spin up)

net $k_\perp^\pi$ (FSI + Collins)



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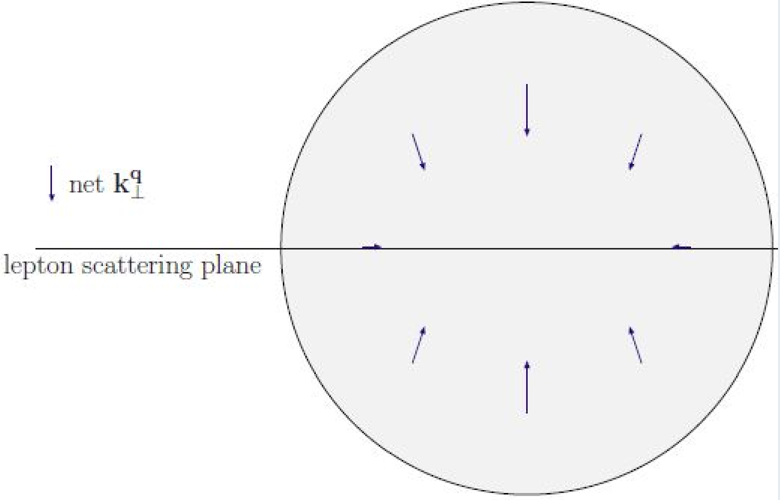

$\cos 2\pi$ modulation of $k_\perp^\pi$

higher twist in polarized DIS

- $\sigma_{LL} \propto g_1 - \frac{2Mx}{\nu} g_2$
- $g_1 = \frac{1}{2}\sum_q e_q^2 g_1^q$ with $g_1^q = q^\uparrow(x) + \bar{q}^\uparrow(x) - q^\downarrow(x) - \bar{q}^\downarrow(x)$
- g_2 involves quark-gluon correlations

$\hookrightarrow$ no parton interpret. as difference between number densities for g_2

- for $\perp$ pol. target, g_1 & g_2 contribute equally

$$\sigma_{LT} \propto g_T \equiv g_1 + g_2$$

$\hookrightarrow$ 'clean' separation between g_2 and $\frac{1}{Q^2}$ corrections to g_1

What can we learn from g_2?

- $g_2 = g_2^{WW} + \bar{g}_2$ with $g_2^{WW}(x) \equiv -g_1(x) + \int_x^1 \frac{dy}{y} g_1(y)$

$$d_2 \equiv 3\int dx\, x^2 \bar{g}_2(x) = \frac{1}{2MP^{+2}S^x} \left\langle P,S \left| \bar{q}(0) g G^{+y}(0)\gamma^+ q(0) \right| P,S \right\rangle$$

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$$\sqrt{2}G^{+y} = G^{0y} + G^{zy} = -E^y + B^x$$

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color Lorentz force MB 2008

$$\sqrt{2} G^{+y} = G^{0y} + G^{zy} = -E^y + B^x = -\left(\vec{E} + \vec{v} \times \vec{B}\right)^y \text{ for } \vec{v} = (0,0,-1)$$

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↪ $d_2 \leftrightarrow$ average **color Lorentz force** acting on quark moving with $v = c$ in $-\hat{z}$ direction in the instant after being struck by γ^*

$$\langle F^y\rangle = -2M^2 d_2 = -\frac{M}{P^{+2}S^x}\left\langle P,S\left|\bar{q}(0)gG^{+y}(0)\gamma^+q(0)\right|P,S\right\rangle$$

cf. Qiu-Sterman matrix element $\langle k_\perp^y\rangle \equiv \int_0^1 dx \int d^2k_\perp\, k_\perp^2 f_{1T}^\perp(x,k_\perp^2)$

$$\langle k_\perp^y\rangle = -\frac{1}{2p^+}\left\langle P,S\left|\bar{q}(0)\int_0^\infty dx^- gG^{+y}(x^-)\gamma^+q(0)\right|P,S\right\rangle$$

semi-classical interpretation: average $k_\perp$ in SIDIS obtained by correlating the quark density with the transverse impulse acquired from (color) Lorentz force acting on struck quark along its trajectory to (light-cone) infinity

matrix element defining d_2 $\leftrightarrow$ 1^{st} integration point in QS-integral

$$d_2 \equiv 3\int dx\, x^2 \bar{g}_2(x) = \frac{1}{2MP^{+2}S^x}\left\langle P,S\left|\bar{q}(0)gG^{+y}(0)\gamma^+q(0)\right|P,S\right\rangle$$

color Lorentz force — MB 2008

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sign of $d_2 \leftrightarrow \perp$ imaging

- $\kappa_q/p \longrightarrow$ sign of deformation

$\hookrightarrow$ direction of average force

$\hookrightarrow$ $d_2^u > 0$, $d_2^d < 0$

- *cf.* $f_{1T}^{\perp u} < 0$, $f_{1T}^{\perp u} < 0$

lattice (Göckeler et al., 2005)

$d_2^u \approx 0.010$, $d_2^d \approx -0.0056$

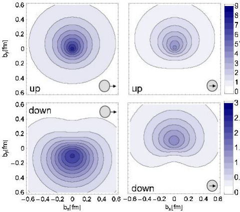
magnitude of d_2

- $\langle F^y\rangle = -2M^2 d_2 = -10\frac{GeV}{fm}d_2$
- expect partial cancellation of forces in SSA

$\hookrightarrow$ $|\langle F^y\rangle| \ll \sigma \approx 1\frac{GeV}{fm}$

$\hookrightarrow$ $d_2 = \mathcal{O}(0.01)$

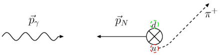
Summary

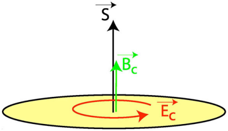


- Deeply Virtual Compton Scattering $\longrightarrow$ GPDs

$\hookrightarrow$ impact parameter dependent PDFs $q(x, \mathbf{b}_\perp)$

- $E^q(x, 0, -\mathbf{\Delta}_\perp^2) \leftrightarrow \kappa_{q/p}$ (contribution from quark flavor q to anomalous magnetic moment)
- $E^q(x, 0, -\mathbf{\Delta}_\perp^2) \longrightarrow \perp$ deformation of PDFs for $\perp$ polarized target
- $\perp$ deformation $\leftrightarrow$ (sign of) SSA (Sivers; Boer-Mulders)
- parton interpretation for Ji-relation
- higher-twist $(\int dx\, x^2 \bar{g}_2(x), \int dx\, x^2 \bar{e}(x)) \leftrightarrow \perp$ force in DIS
- $\perp$ deformation $\leftrightarrow$ (sign of) quark-gluon correlations $(\int dx\, x^2 \bar{g}_2(x), \int dx\, x^2 \bar{e}(x)\ )$





combine complementary information from deeply-virtual Compton scattering, semi-inclusive DIS & Drell-Yan to study orbital angular momentum and map the 3-d structure of hadrons

Q^2 scaling for Compton form factor (JLab)