Transverse Force Tomography

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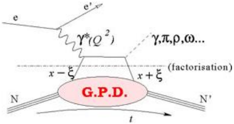


- GPDs $\longrightarrow$ 3D imaging of the nucleon
- twist-3 PDFs $g_2(x) \longrightarrow$ $\perp$ force

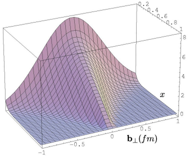
$\hookrightarrow$ twist-3 GPDs $\longrightarrow$ $\perp$ force tomography

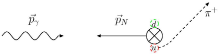
Motivation: why twist-3 GPDs

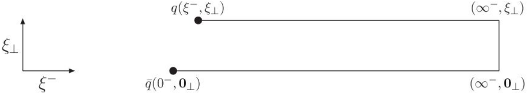
- twist-3 GPD $G_2^q \longrightarrow L^q$
- twist 3 PDF $g_2(x) \longrightarrow \perp$ force
- twist 2 GPDs $\longrightarrow \perp$ imaging (of quark densities)

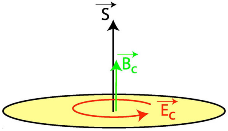
$\hookrightarrow$ twist 3 GPDs $\longrightarrow$ $\perp$ imaging of $\perp$ forces

- Summary



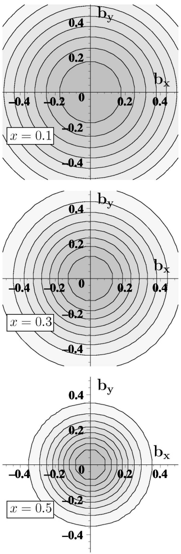


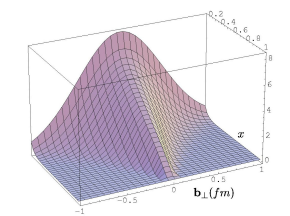


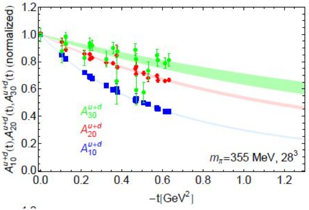


Physics of GPDs: 3D Imaging MB,PRD 62, 071503 (2000)

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







unpolarized proton

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

$\hookrightarrow$ probabilistic interpretation

- no relativistic corrections
- $F_1(-\mathbf{\Delta}_\perp^2) = \int dx H(x, 0, -\mathbf{\Delta}_\perp^2)$
- x = momentum fraction of the quark
- $\mathbf{b}_\perp$ relative to $\perp$ center of momentum
- small x: large 'meson cloud'
- larger x: compact 'valence core'
- $x \to 1$: active quark = center of momentum

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

MB, PRD62, 071503 (2000)

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

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

Impact Parameter Dependent Quark Distributions

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

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

- probabilistic interpretation!
- no relativistic corrections: Galilean subgroup! (MB,2000)

$\hookrightarrow$ corollary: interpretation of 2d-FT of $F_1(Q^2)$ as charge density in transverse plane also free from relativistic corrections (MB, 2003; G.A.Miller, 2007)

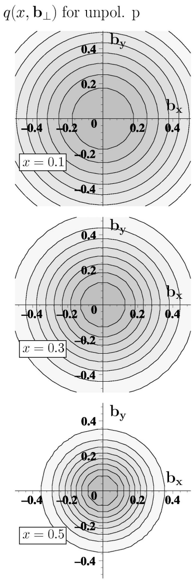
$\perp$ localized state

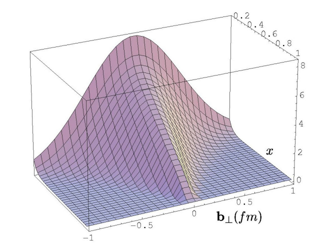
$$|\mathbf{R}_\perp = 0, p^+, \Lambda\rangle \equiv \mathcal{N} \int d^2\mathbf{p}_\perp |\mathbf{p}_\perp, p^+, \Lambda\rangle$$

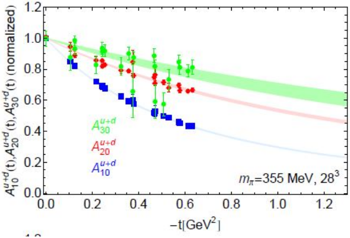
$\perp$ charge distribution (unpolarized quarks)

$$\begin{aligned}
\rho_{\Lambda'\Lambda}(\mathbf{b}_\perp) &\equiv \langle \mathbf{R}_\perp = 0, p^+, \Lambda' | \bar{q}(\mathbf{b}_\perp)\gamma^+ q(\mathbf{b}_\perp) | \mathbf{R}_\perp = 0, p^+, \Lambda\rangle \\
&= |\mathcal{N}|^2 \int d^2\mathbf{p}_\perp \int d^2\mathbf{p}'_\perp \langle \mathbf{p}'_\perp, p^+, \Lambda' | \bar{q}(0)\gamma^+ q(0) | \mathbf{p}_\perp, p^+, \Lambda\rangle e^{i\mathbf{b}_\perp\cdot(\mathbf{p}_\perp - \mathbf{p}'_\perp)} \\
&= |\mathcal{N}|^2 \int d^2\mathbf{P}_\perp \int d^2\mathbf{\Delta}_\perp \langle \mathbf{p}'_\perp, p^+, \Lambda' | \bar{q}(0)\gamma^+ q(0) | \mathbf{p}_\perp, p^+, \Lambda\rangle e^{i\mathbf{b}_\perp\cdot(\mathbf{p}_\perp - \mathbf{p}'_\perp)} \\
&= \int d^2\mathbf{\Delta}_\perp F_{\Lambda'\Lambda}(-\mathbf{\Delta}_\perp^2) e^{-i\mathbf{b}_\perp\cdot\mathbf{\Delta}_\perp}
\end{aligned}$$

- crucial: $\langle \mathbf{p}'_\perp, p^+, \Lambda' | \bar{q}(0)\gamma^+ q(0) | \mathbf{p}_\perp, p^+, \Lambda\rangle$ depends only on $\mathbf{\Delta}_\perp$
- $F_{\Lambda'\Lambda}(-\mathbf{\Delta}_\perp^2)$ some linear combination of F_1 & F_2 - depending on Λ, Λ'
- similar for various polarized quark densities







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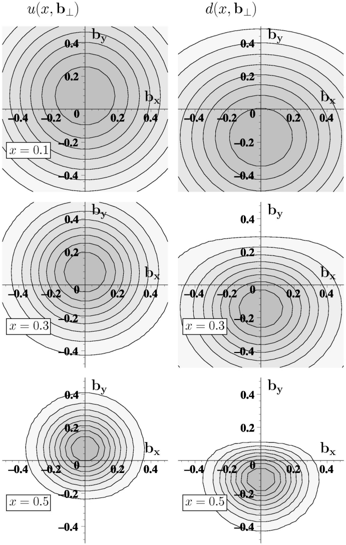
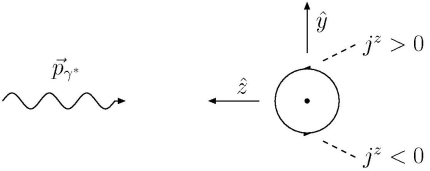
Physics of GPDs: 3D Imaging MB, IJMPA 18, 173 (2003)





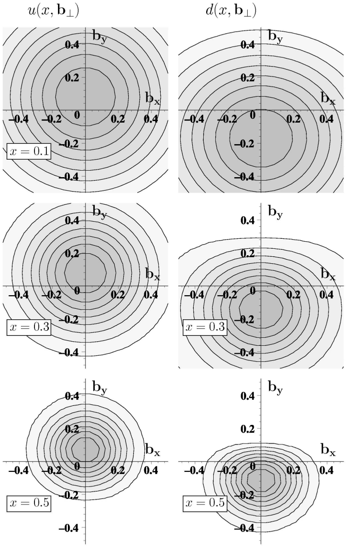
proton polarized in $+\hat{x}$ direction

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

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

- relevant density in DIS is $j^+ \equiv j^0 + j^z$ and left-right asymmetry from j^z
- av. shift model-independently related to anomalous magnetic moments:

$$\langle b_y^q \rangle \equiv \int dx \int d^2 b_\perp q(x,\mathbf{b}_\perp) b_y = \frac{1}{2M}\int dx E_q(x,0,0) = \frac{\kappa_q}{2M}$$



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

no axial symmetry!

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

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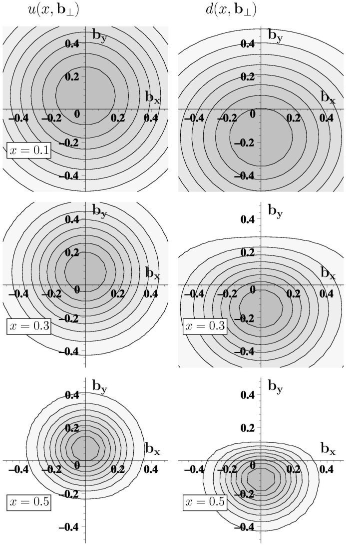
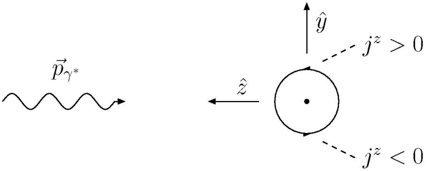
Physics: relevant density in DIS is $j^+ \equiv j^0 + j^3$ and left-right asymmetry from j^3

intuitive explanation

- moving Dirac particle with anomalous magnetic moment has electric dipole moment $\perp$ to $\vec{p}$ and $\perp$ magnetic moment

$\hookrightarrow$ γ^* 'sees' flavor dipole moment of oncoming nucleon



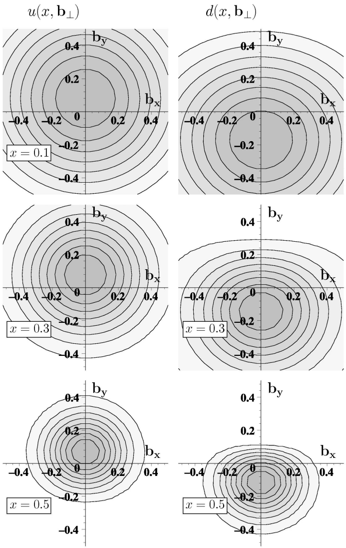


proton polarized in $+\hat{x}$ direction

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 DIS is $j^+ \equiv j^0 + j^3$ and left-right asymmetry from j^3



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

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

sign & magnitude of the average shift

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

$$\langle b_y^q \rangle \equiv \int dx \int d^2 b_\perp q(x, \mathbf{b}_\perp) b_y = \frac{1}{2M} \int dx E_q(x, 0) = \frac{\kappa_q}{2M}$$

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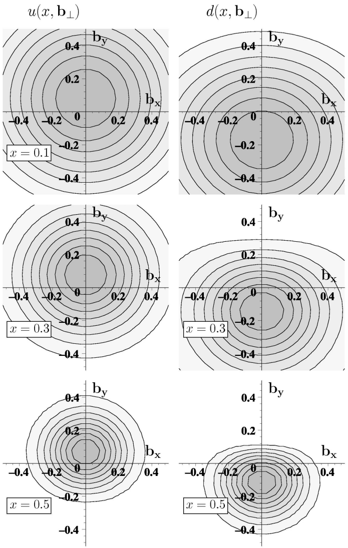

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$$\kappa^p = 1.913 = \frac{2}{3}\kappa_u^p - \frac{1}{3}\kappa_d^p + \ldots$$

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

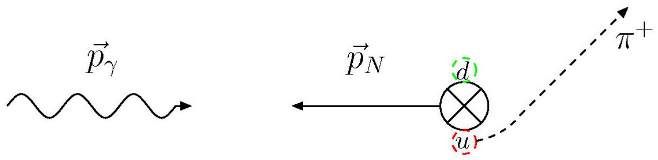
$\hookrightarrow$ shift in $+\hat{y}$ direction

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

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

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

example: $\gamma p \to \pi X$



- 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 final state interaction (FSI) deflects active quark towards the center of momentum

$\hookrightarrow$ 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,2004)

- confirmed by HERMES & COMPASS data

This is not stamp collecting

- twist 3 may have to be included to fit JLab data
- twist 3 necessary to understand what makes nucleon structure

$\hookrightarrow$ need to understand 'the force'

- alternative angular momentum sum rule (M.Polyakov)
- transverse force tomography (this talk)
- there's really weird stuff going on at twist 3
  (F.Aslan + M.B. arXiv:1811.00938)

yes, this will be hard, but...

- lattice QCD can provide (genuine) twist 3 info much sooner

$d_2 \leftrightarrow$ average $\perp$ force on quark in DIS from $\perp$ pol target

polarized DIS:

- $\sigma_{LL} \propto g_1 - \frac{2Mx}{\nu} g_2$
- $\sigma_{LT} \propto g_T \equiv g_1 + g_2$

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

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

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

color Lorentz Force on ejected quark (MB, PRD 88 (2013) 114502)

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

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

sign of d_2

- $\perp$ deformation of $q(x, \mathbf{b}_\perp)$

$\hookrightarrow$ sign of d_2^q: opposite Sivers

magnitude of d_2

- $\langle F^y \rangle = -2M^2 d_2 = -10 \frac{GeV}{fm} d_2$
- $|\langle F^y \rangle| \ll \sigma \approx 1 \frac{GeV}{fm} \Rightarrow d_2 = \mathcal{O}(0.01)$

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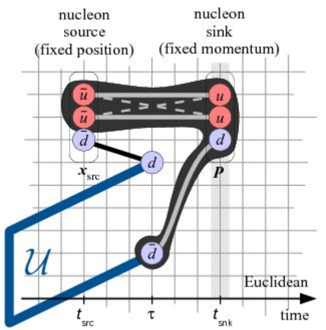
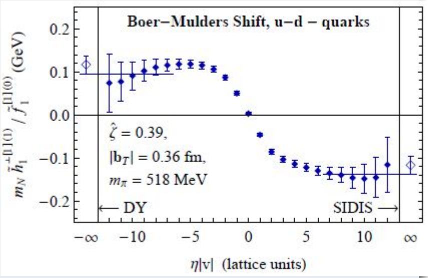
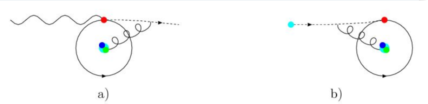
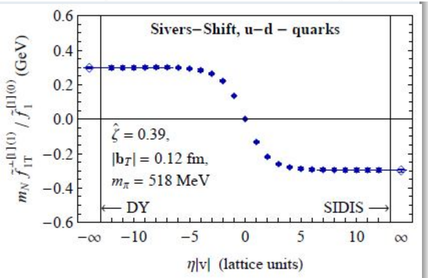
- $|\langle F^y \rangle| \ll \sigma \approx 1 \frac{GeV}{fm} \Rightarrow d_2 = \mathcal{O}(0.01)$

consitent with experiment (JLab,SLAC), model calculations (Weiss), and lattice QCD calculations (Göckeler et al., 2005)









$f_{1T}^{\perp}(x, \mathbf{k}_\perp)$ is $\mathbf{k}_\perp$-odd term in quark-spin averaged momentum distribution in $\perp$ polarized target

The Force

slope at length $=0$

chirally even spin-dependent twist-3 PDF $g_2(x)$

MB, PRD 88 (2013) 114502

- $\int dx\, x^2 g_2(x) \Rightarrow\perp$ force on unpolarized quark in $\perp$ polarized target

$\hookrightarrow$ 'Sivers force'

scalar twist-3 PDF $e(x)$

MB, PRD 88 (2013) 114502

- $\int dx\, x^2 e(x) \Rightarrow\perp$ force on $\perp$ polarized quark in unpolarized target

$\hookrightarrow$ 'Boer-Mulders force'

chirally odd spin-dependent twist-3 PDF $h_2(x)$

M.Abdallah & MB, PRD94 (2016) 094040

- $\int dx\, x^2 h_2(x) = 0$

$\hookrightarrow$ $\perp$ force on $\perp$ pol. quark in long. pol. target vanishes due to parity

- $\int dx\, x^3 h_2(x) \Rightarrow$ long. gradient of $\perp$ force on $\perp$ polarized quark in long. polarized target

$\hookrightarrow$ chirally odd 'wormgear force'

Where 'the Force' matters

- Sivers: $\perp$ (target) SSA in SIDIS from FSI
- Boer-Mulders: $\cos 2\phi$ asymmetry in π production on unpolarized target

$\hookrightarrow$ All TMDs!

- Jaffe-Manohar *vs.* Ji orbital angular momentum

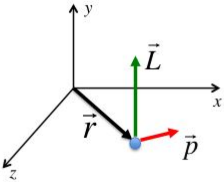
Digression: Angular Momentum Carried by Quarks

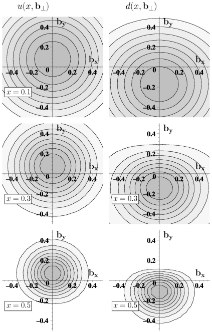
- Wigner functions!
  $L_z = \int dx \int d^2 b_\perp \int d^2 k_\perp (b_x k_y - b_y k_x)\, W(x, \mathbf{b}_\perp, \mathbf{k}_\perp)$
- Alternative: $L_x = y p_z - z p_y$
- if state invariant under rotations about $\hat{x}$ axis then $\langle y p_z \rangle = -\langle z p_y \rangle$

$\hookrightarrow$ $\langle L_x \rangle = 2 \langle y p_z \rangle$

- GPDs provide simultaneous information about longitudinal momentum and transverse position

$\hookrightarrow$ use quark GPDs to determine angular momentum carried by quarks





Ji sum rule (1996)

$$J_q^x = \frac{1}{2} \int dx\, x \left[H(x,0,0) + E(x,0,0) \right]$$

- parton interpretation in terms of 3D distributions only for $\perp$ component
  (MB,2001,2005)

QED with electrons

$$\begin{aligned}\vec{J}_\gamma &= \int d^3r\,\vec{r}\times\left(\vec{E}\times\vec{B}\right) = \int d^3r\,\vec{r}\times\left[\vec{E}\times\left(\vec{\nabla}\times\vec{A}\right)\right] \\ &= \int d^3r\left[E^j\left(\vec{r}\times\vec{\nabla}\right)A^j - \vec{r}\times(\vec{E}\cdot\vec{\nabla})\vec{A}\right] \\ &= \int d^3r\left[E^j\left(\vec{r}\times\vec{\nabla}\right)A^j + \left(\vec{r}\times\vec{A}\right)\vec{\nabla}\cdot\vec{E} + \vec{E}\times\vec{A}\right]\end{aligned}$$

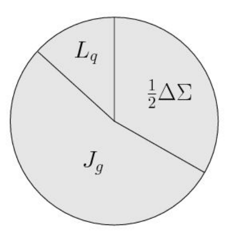
- replace 2^{nd} term (eq. of motion $\vec{\nabla}\cdot\vec{E} = ej^0 = e\psi^\dagger\psi$), yielding

$$\vec{J}_\gamma = \int d^3r\left[\psi^\dagger\vec{r}\times e\vec{A}\psi + E^j\left(\vec{x}\times\vec{\nabla}\right)A^j + \vec{E}\times\vec{A}\right]$$

- $\psi^\dagger\vec{r}\times e\vec{A}\psi$ cancels similar term in electron OAM $\psi^\dagger\vec{r}\times(\vec{p}-e\vec{A})\psi$

$\hookrightarrow$ decomposing $\vec{J}_\gamma$ into spin and orbital also shuffles angular momentum from photons to electrons!

Ji decomposition



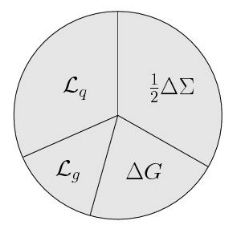
'pizza tre stagioni'

$$\frac{1}{2} = \sum_q \left(\frac{1}{2}\Delta q + L_q\right) + J_g$$

$$L_q = \int d^3x \langle P,S| q^\dagger(\vec{x}) \left(\vec{x} \times i\vec{D}\right)^3 q(\vec{x}) |P,S\rangle$$

- $i\vec{D} = i\vec{\partial} - g\vec{A}$
- DVCS $\longrightarrow$ GPDs $\longrightarrow L^q$

Jaffe-Manohar decomposition



'pizza quattro stagioni'

$$\frac{1}{2} = \sum_q \left(\frac{1}{2}\Delta q + \mathcal{L}_q\right) + \Delta G + \mathcal{L}_g$$

$$\mathcal{L}_q = \int d^3r \langle P,S| \bar{q}(\vec{r})\gamma^+ \left(\vec{r} \times i\vec{\partial}\right)^z q(\vec{r}) |P,S\rangle$$

- light-cone gauge $A^+ = 0$
- $\vec{p}\,\overleftarrow{p} \longrightarrow \Delta G \longrightarrow \mathcal{L} \equiv \sum_{i\in q,g} \mathcal{L}^i$
- manifestly gauge inv. def. exists

How large is difference $\mathcal{L}_q - L_q$ in QCD and what does it represent?

- in Bjorken limit, many relevant observables (PDFs, GPDs, TMDs) equal x^+ correlators

$\hookrightarrow$ consider 6-D Wigner functions

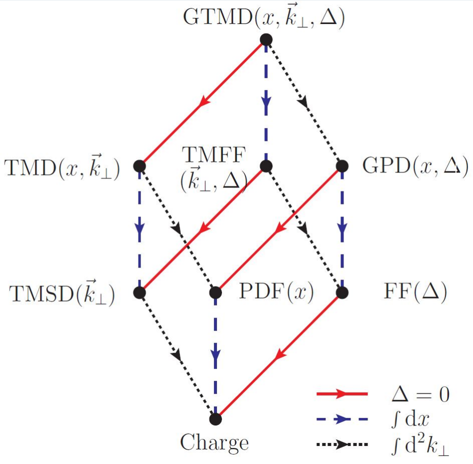
6-D Wigner Functions (Belitsky, Ji, Yuan)?

- indroduced Wigner functions that depend on $k^+, \vec{k}_\perp, \xi^-, \vec{\xi}_\perp$
- so far no insights from ξ^- dependence

$\hookrightarrow$ throw away that information ($\int d\xi^-$)

$\hookrightarrow$ 5-D Wigner functions

5-D Wigner Functions (Lorcé, Pasquini)



$$W(x, \vec{b}_\perp, \vec{k}_\perp) \equiv \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} e^{-i\vec{\Delta}_\perp \cdot \vec{b}_\perp} GTMD(x, \vec{k}_\perp, \vec{\Delta}_\perp)$$

Quark OAM from Wigner Functions

5-D Wigner Functions (Lorcé, Pasquini)

$$W(x,\vec{b}_\perp,\vec{k}_\perp) \equiv \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} \int \frac{d^2\xi_\perp d\xi^-}{(2\pi)^3} e^{ik\cdot\xi} e^{-i\vec{\Delta}_\perp\cdot\vec{b}_\perp} \langle P'S'|\bar{q}(0)\gamma^+ q(\xi)|PS\rangle.$$

- TMDs: $f(x,\mathbf{k}_\perp) = \int d^2\mathbf{b}_\perp W(x,\vec{b}_\perp,\vec{k}_\perp)$
- GPDs: $q(x,\mathbf{b}_\perp) = \int d^2\mathbf{k}_\perp W(x,\vec{b}_\perp,\vec{k}_\perp)$
- $L_z = \int dx \int d^2\mathbf{b}_\perp \int d^2\mathbf{k}_\perp W(x,\vec{b}_\perp,\vec{k}_\perp)(b_x k_y - b_y k_x)$
- need to include Wilson-line gauge link $\mathcal{U}_{0\xi} \sim \exp\left(i\frac{g}{\hbar}\int_0^\xi \vec{A}\cdot d\vec{r}\right)$ to connect 0 and ξ

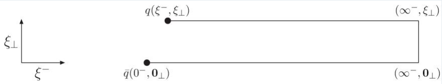
$\hookrightarrow$ 'light-cone staple' crucial for SSAs in SIDIS & DY

straight line for $\mathcal{U}_{0\xi}$

straigth Wilson line from 0 to ξ yields Ji-OAM:

$$L^q = \int d^3x \langle P,S|q^\dagger(\vec{x})\left(\vec{x}\times i\vec{D}\right)^z q(\vec{x})|P,S\rangle$$

Light-Cone Staple for $\mathcal{U}_{0\xi}$



'light-cone staple' yields $\mathcal{L}_{Jaffe-Manohar}$

$\mathcal{L}_{\sqsupset}/\mathcal{L}_{\sqsubset}$

$\mathcal{L}$ with light-cone staple at $x^- = \pm\infty$

PT (Hatta)

- PT$\longrightarrow$ $\mathcal{L}_{\sqsupset} = \mathcal{L}_{\sqsubset}$

(different from SSAs due to factor $\vec{x}$ in OAM)

Bashinsky-Jaffe

- $A^+ = 0$ no complete gauge fixing

$\hookrightarrow$ residual gauge inv. $A^\mu \to A^\mu + \partial^\mu \phi(\vec{x}_\perp)$

- $\vec{x} \times i\vec{\partial} \quad \to \quad \mathcal{L}_{JB} \equiv \vec{x} \times \left[i\vec{\partial} - g\vec{\mathcal{A}}(\vec{x}_\perp) \right]$
- $\vec{\mathcal{A}}_\perp(\vec{x}_\perp) = \frac{\int dx^- \vec{A}_\perp(x^-, \vec{x}_\perp)}{\int dx^-}$

Bashinsky-Jaffe $\leftrightarrow$ light-cone staple

- $A^+ = 0$

$\hookrightarrow$ $\mathcal{L}_{\sqsupset/\sqsubset} = \vec{x} \times \left[i\vec{\partial} - g\vec{A}_\perp(\pm\infty, \vec{x}_\perp) \right]$

- $\mathcal{L}_{JB} = \vec{x} \times \left[i\vec{\partial} - g\vec{\mathcal{A}}(\vec{x}_\perp) \right]$
- $\vec{\mathcal{A}}_\perp(\vec{x}_\perp) = \frac{\int dx^- \vec{A}_\perp(x^-, \vec{x}_\perp)}{\int dx^-} = \frac{1}{2}\left(\vec{A}_\perp(\infty, \vec{x}_\perp) + \vec{A}_\perp(-\infty, \vec{x}_\perp) \right)$

$\hookrightarrow$ $\mathcal{L}_{JB} = \frac{1}{2}\left(\mathcal{L}_{\sqsupset} + \mathcal{L}_{\sqsubset}\right) = \mathcal{L}_{\sqsupset} = \mathcal{L}_{\sqsubset}$

straight line ($\rightarrow$Ji)

$$\frac{1}{2} = \sum_q \frac{1}{2}\Delta q + L_q + J_g$$

$$L_q = \int d^3x \langle P,S|\bar{q}(\vec{x})\gamma^+\left(\vec{x}\times i\vec{D}\right)^z q(\vec{x})|P,S\rangle$$

- $i\vec{D} = i\vec{\partial} - g\vec{A}$

light-cone staple ($\rightarrow$ Jaffe-Manohar)

$$\frac{1}{2} = \sum_q \frac{1}{2}\Delta q + \mathcal{L}_q + \Delta G + \mathcal{L}_g$$

$$\mathcal{L}^q = \int d^3x \langle P,S|\bar{q}(\vec{x})\gamma^+\left(\vec{x}\times i\vec{\mathcal{D}}\right)^z q(\vec{x})|P,S\rangle$$

$$i\vec{\mathcal{D}} = i\vec{\partial} - g\vec{A}(x^- = \infty, \mathbf{x}_\perp)$$

difference $\mathcal{L}^q - L^q$

$$\mathcal{L}^q - L^q = -g\int d^3x \langle P,S|\bar{q}(\vec{x})\gamma^+\left[\vec{x}\times \int_{x^-}^{\infty} dr^- F^{+\perp}(r^-,\mathbf{x}_\perp)\right]^z q(\vec{x})|P,S\rangle$$

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

straight line ($\rightarrow$Ji)

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$$i\mathcal{D}^j = i\partial^j - gA^j(x^-,\mathbf{x}_\perp) - g\int_{x^-}^\infty dr^- F^{+j}$$

difference $\mathcal{L}^q - L^q$

$$\mathcal{L}^q - L^q = -g\int d^3x \langle P,S|\bar{q}(\vec{x})\gamma^+\left[\vec{x}\times\int_{x^-}^\infty dr^- F^{+\perp}(r^-,\mathbf{x}_\perp)\right]^z q(\vec{x})|P,S\rangle$$

color Lorentz Force on ejected quark (MB, PRD 88 (2013) 014014)

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

Quark OAM from Wigner Functions

straight line (→Ji)

$$\frac{1}{2} = \sum_q \frac{1}{2}\Delta q + L_q + J_g$$

$$L_q = \int d^3x \langle P,S|\bar{q}(\vec{x})\gamma^+\left(\vec{x}\times i\vec{D}\right)^z q(\vec{x})|P,S\rangle$$

- $i\vec{D} = i\vec{\partial} - g\vec{A}$

light-cone staple (→ Jaffe-Manohar)

$$\frac{1}{2} = \sum_q \frac{1}{2}\Delta q + \mathcal{L}_q + \Delta G + \mathcal{L}_g$$

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difference $\mathcal{L}^q - L^q$

$$\mathcal{L}^q - L^q = -g\int d^3x \langle P,S|\bar{q}(\vec{x})\gamma^+\left[\vec{x}\times\int_{x^-}^\infty dr^- F^{+\perp}(r^-,\mathbf{x}_\perp)\right]^z q(\vec{x})|P,S\rangle$$

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Torque along the trajectory of q

$$T^z = \left[\vec{x}\times\left(\vec{E} - \hat{\vec{z}}\times\vec{B}\right)\right]^z$$

Change in OAM

$$\Delta L^z = \int_{x^-}^\infty dr^- \left[\vec{x}\times\left(\vec{E} - \hat{\vec{z}}\times\vec{B}\right)\right]^z$$

difference $\mathcal{L}^q - L^q$

$\mathcal{L}^q_{JM} - L^q_{Ji} = \Delta L^q_{FSI} =$ change in OAM as quark leaves nucleon

$$\mathcal{L}^q_{JM} - L^q_{Ji} = -g\int d^3x \langle P,S|\bar{q}(\vec{x})\gamma^+\left[\vec{x}\times\int_{x^-}^{\infty} dr^- F^{+\perp}(r^-,\mathbf{x}_\perp)\right]^z q(\vec{x})|P,S\rangle$$

e^+ moving through dipole field of e^-

- consider e^- polarized in $+\hat{z}$ direction

$\hookrightarrow$ $\vec{\mu}$ in $-\hat{z}$ direction (Figure)

- e^+ moves in $-\hat{z}$ direction

$\hookrightarrow$ net torque negative

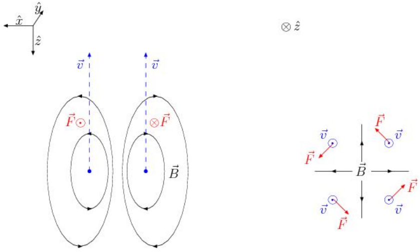
sign of $\mathcal{L}^q - L^q$ in QCD

- color electric force between two q in nucleon attractive

$\hookrightarrow$ same as in positronium

- spectator spins positively correlated with nucleon spin

$\hookrightarrow$ expect $\mathcal{L}^q - L^q < 0$ in nucleon



a.) b.)

difference $\mathcal{L}^q - L^q$

$\mathcal{L}^q_{JM} - L^q_{Ji} = \Delta L^q_{FSI}$ = change in OAM as quark leaves nucleon

$$\mathcal{L}^q_{JM} - L^q_{Ji} = -g\int d^3x \langle P,S|\bar{q}(\vec{x})\gamma^+\left[\vec{x}\times\int_{x^-}^{\infty} dr^- F^{+\perp}(r^-,\mathbf{x}_\perp)\right]^z q(\vec{x})|P,S\rangle$$

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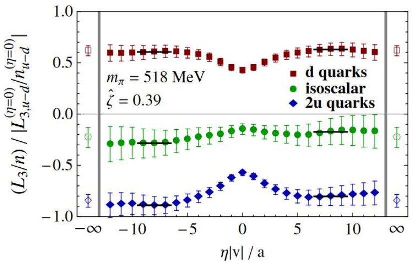
$\hookrightarrow$ expect $\mathcal{L}^q - L^q < 0$ in nucleon

lattice QCD M.Engelhardt et al.

- L_{staple} vs. staple length

$\hookrightarrow$ L^q_{Ji} for length $= 0$

$\hookrightarrow$ $\mathcal{L}^q_{JM}$ for length $\to \infty$



$\perp$ force distribution (unpolarized quarks)

$$F^i_{\Lambda'\Lambda}(\mathbf{b}_\perp) \equiv \langle \mathbf{R}_\perp = 0, p^+, \Lambda' | \bar{q}(\mathbf{b}_\perp)\gamma^+ g F^{+i}(\mathbf{b}_\perp) q(\mathbf{b}_\perp) | \mathbf{R}_\perp = 0, p^+, \Lambda\rangle$$
$$= |\mathcal{N}|^2 \int d^2\mathbf{p}_\perp \int d^2\mathbf{p}'_\perp \langle \mathbf{p}'_\perp, p^+, \Lambda | \bar{q}(0)\gamma^+ g F^{+i}(0) q(0) | \mathbf{p}_\perp, p^+, \Lambda\rangle e^{i\mathbf{b}_\perp\cdot(\mathbf{p}_\perp - \mathbf{p}'_\perp)}$$

Form factors of qgq correlator (F.Aslan, M.B., M.Schlegel arXiv:1904.03494)

$$\begin{aligned}
\langle p', \lambda' | \bar{q}(0)\gamma^+ i g G^{+i}(0) q(0) | p, \lambda\rangle &= \bar{u}(p', \lambda')\Big\{ \frac{1}{M^2}[P^+\Delta^i_\perp - P^\perp \Delta^+)]\gamma^+ \Phi_1(t) \quad (1)\\
+\frac{P^+}{M} i\sigma^{+i}\Phi_2(t) &+ \frac{1}{M^3} i\sigma^{+\Delta}\left[P^+\Delta^i_\perp \Phi_3(t) - P^\perp \Delta^+ \Phi_4(t)\right]\\
&+ \frac{P^+\Delta^+}{M^3} i\sigma^{i\Delta}\Phi_5(t)\Big\} u(p, \lambda)
\end{aligned}$$

crucial:

- for $p^{+\prime} = p^+$, $\langle p', \lambda' | \bar{q}(0)\gamma^+ i g F^{+i}(0) q(0) | p, \lambda\rangle$ only depends on $\mathbf{\Delta}_\perp$

$\hookrightarrow$ similar to $\perp$ charge density ...

$\perp$ force distribution (unpolarized quarks)

$$
\begin{aligned}
F^i_{\Lambda'\Lambda}(\mathbf{b}_\perp) &\equiv \langle \mathbf{R}_\perp = 0, p^+, \Lambda' | \bar{q}(\mathbf{b}_\perp)\gamma^+ g F^{+i}(\mathbf{b}_\perp) q(\mathbf{b}_\perp) | \mathbf{R}_\perp = 0, p^+, \Lambda\rangle \\
&= |\mathcal{N}|^2 \int d^2\mathbf{p}_\perp \int d^2\mathbf{p}'_\perp \langle \mathbf{p}'_\perp, p^+, \Lambda | \bar{q}(0)\gamma^+ g F^{+i}(0) q(0) | \mathbf{p}_\perp, p^+, \Lambda\rangle e^{i\mathbf{b}_\perp\cdot(\mathbf{p}_\perp - \mathbf{p}'_\perp)}
\end{aligned}
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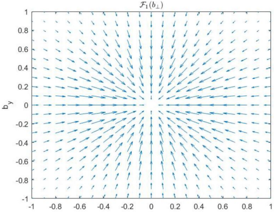
&+ \frac{P^+\Delta^+}{M^3} i\sigma^{i\Delta}\Phi_5(t)\Big\} u(p, \lambda)
\end{aligned}
$$

Φ_1

- unpolarized target
- axially symmetric 'radial' force



$\perp$ force distribution (unpolarized quarks)

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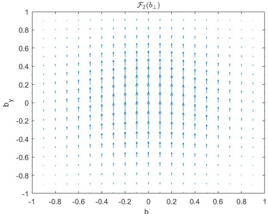
+\frac{P^+}{M} i\sigma^{+i}\Phi_2(t) &+ \frac{1}{M^3} i\sigma^{+\Delta}\left[P^+\Delta^i_\perp\Phi_3(t) - P^\perp\Delta^+\Phi_4(t)\right] \\
&+ \frac{P^+\Delta^+}{M^3} i\sigma^{i\Delta}\Phi_5(t)\Big\} u(p, \lambda)
\end{aligned}$$

Φ_2

- $\perp$ polarized target; force $\perp$ to target spin

$\hookrightarrow$ spatially resolved Sivers force



$\perp$ force distribution (unpolarized quarks)

$$F^i_{\Lambda'\Lambda}(\mathbf{b}_\perp) \equiv \langle \mathbf{R}_\perp = 0, p^+, \Lambda' | \bar{q}(\mathbf{b}_\perp)\gamma^+ gF^{+i}(\mathbf{b}_\perp)q(\mathbf{b}_\perp)|\mathbf{R}_\perp = 0, p^+, \Lambda\rangle$$
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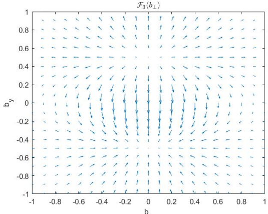
Form factors of qgq correlator (F.Aslan, M.B., M.Schlegel arXiv:1904.03494)

$$\begin{aligned}\langle p', \lambda' | \bar{q}(0)\gamma^+ igG^{+i}(0)q(0)|p,\lambda\rangle &= \overline{u}(p',\lambda')\Big\{ \frac{1}{M^2}[P^+\Delta^i_\perp - P^\perp\Delta^+)]\gamma^+\Phi_1(t)(1) \\ +\frac{P^+}{M} i\sigma^{+i}\Phi_2(t) &+ \frac{1}{M^3} i\sigma^{+\Delta}\left[P^+\Delta^i_\perp \Phi_3(t) - P^\perp \Delta^+ \Phi_4(t)\right] \\ &+ \frac{P^+\Delta^+}{M^3} i\sigma^{i\Delta}\Phi_5(t)\Big\} u(p,\lambda)\end{aligned}$$

Φ_3

- tensor type force
- similar to charged particle flying through magnetic dipole field



$\perp$ force distribution (unpolarized quarks)

$$
\begin{aligned}
F^i_{\Lambda'\Lambda}(\mathbf{b}_\perp) &\equiv \langle \mathbf{R}_\perp = 0, p^+, \Lambda' | \bar{q}(\mathbf{b}_\perp)\gamma^+ g F^{+i}(\mathbf{b}_\perp) q(\mathbf{b}_\perp) | \mathbf{R}_\perp = 0, p^+, \Lambda\rangle \\
&= |\mathcal{N}|^2 \int d^2\mathbf{p}_\perp \int d^2\mathbf{p}'_\perp \langle \mathbf{p}'_\perp, p^+, \Lambda | \bar{q}(0)\gamma^+ g F^{+i}(0) q(0) | \mathbf{p}_\perp, p^+, \Lambda\rangle e^{i\mathbf{b}_\perp\cdot(\mathbf{p}_\perp - \mathbf{p}'_\perp)}
\end{aligned}
$$

Form factors of qgq correlator (F.Aslan, M.B., M.Schlegel arXiv:1904.03494)

$$
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\langle p', \lambda' | \bar{q}(0)\gamma^+ i g G^{+i}(0) q(0) | p, \lambda\rangle &= \bar{u}(p', \lambda')\Big\{ \frac{1}{M^2}[P^+\Delta^i_\perp - P^\perp\Delta^+)]\gamma^+\Phi_1(t)\quad(1) \\
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&+ \frac{P^+\Delta^+}{M^3} i\sigma^{i\Delta}\Phi_5(t)\Big\} u(p, \lambda)
\end{aligned}
$$

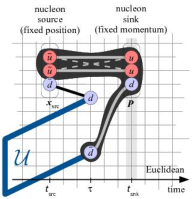
Φ_4, Φ_5

- no conmtribution for $\Delta^+ = 0$

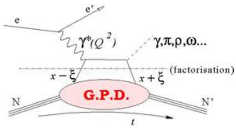
determining Φ_i

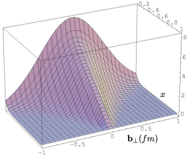
- match with x^2 moments of twist-3 GPDs (minus WW parts)
  F.Aslan, M.B. in progress
- experiments may take a few years, or immediately
- lattice QCD: fit to nonforward matrix elements of 'the force'-operator
  in progress (J.Bickerton, R.Young, J.Zanotti)

the force operator



- form factor with quark denstity involving Wilson line staple
- take derivative w.r.t. staple length at length =0

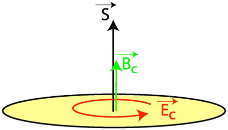


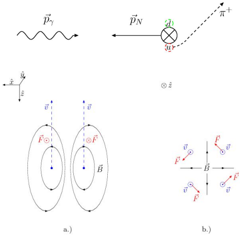


- GPDs $\xrightarrow{FT} q(x, \mathbf{b}_\perp)$ '3d imaging'
- x^2 moment of twist-3 PDFs $\rightarrow$ force
- x^2 moment of twist-3 GPDs

$\hookrightarrow$ $\bar{q}\gamma^+ F^{+\perp}\Gamma q$ distribution

$\hookrightarrow$ $\perp$ force tomography





Summary

- GPDs $\xrightarrow{FT}$ $q(x, \mathbf{b}_\perp)$ '3d imaging'
- x^2 moment of twist-3 PDFs $\rightarrow$ force
- x^2 moment of twist-3 GPDs

$\hookrightarrow$ $\bar{q}\gamma^+ F^{+\perp}\Gamma q$ distribution

$\hookrightarrow$ $\perp$ force tomography