PARTON OAM: EXPERIMENTAL LEADS

7^{TH} GHP WORKSHOP
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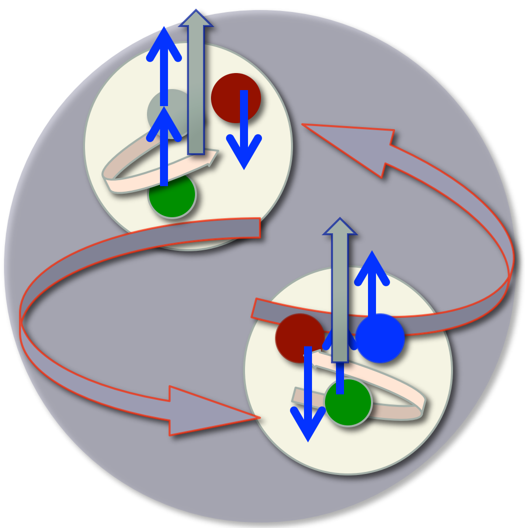

Based on

PHYSICAL REVIEW D **94**, 034041 (2016)

Parton transverse momentum and orbital angular momentum distributions

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The quark orbital angular momentum component of proton spin, L_q, can be defined in QCD as the integral of a Wigner phase space distribution weighting the cross product of the quark's transverse position and momentum. It can also be independently defined from the operator product expansion for the off-forward Compton amplitude in terms of a twist-three generalized parton distribution. We provide an explicit link between the two definitions, connecting them through their dependence on partonic intrinsic transverse momentum. Connecting the definitions provides the key for correlating direct experimental determinations of L_q and evaluations through lattice QCD calculations. The direct observation of quark orbital angular momentum does not require transverse spin polarization but can occur using longitudinally polarized targets.

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…and A. Rajan et al., soon to be posted

Outline

1. Definitions
2. Lorentz Invariant Relations ➔OAM is given by a twist three distribution
3. Equations of Motion Relations
4. A probe of QCD at the amplitude level
5. Process dependence of OAM distributions/universality
6. Conclusions

1. DEFINITIONS

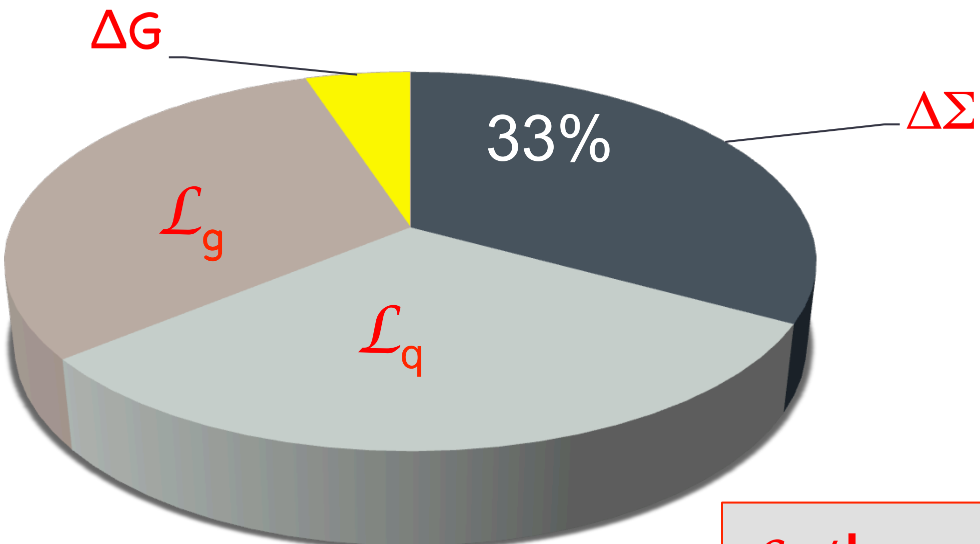
The spin crisis in a cartoon

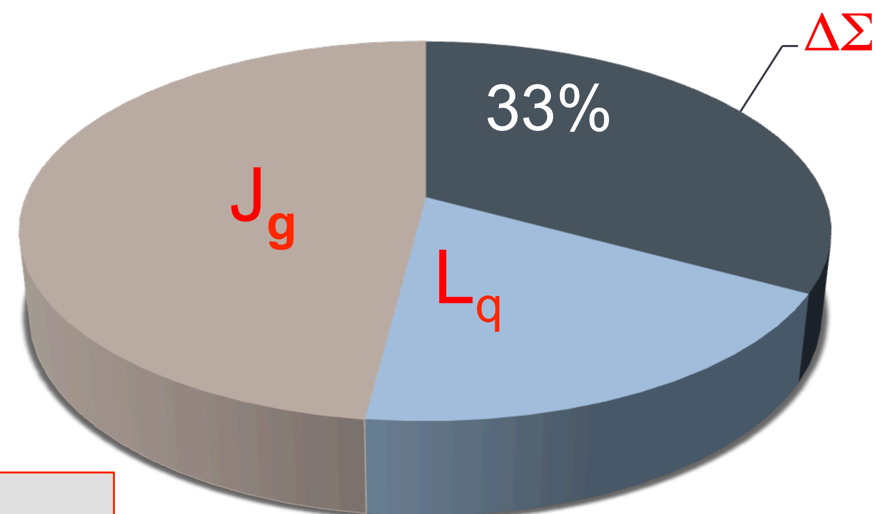
Jaffe Manohar

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

Ji

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

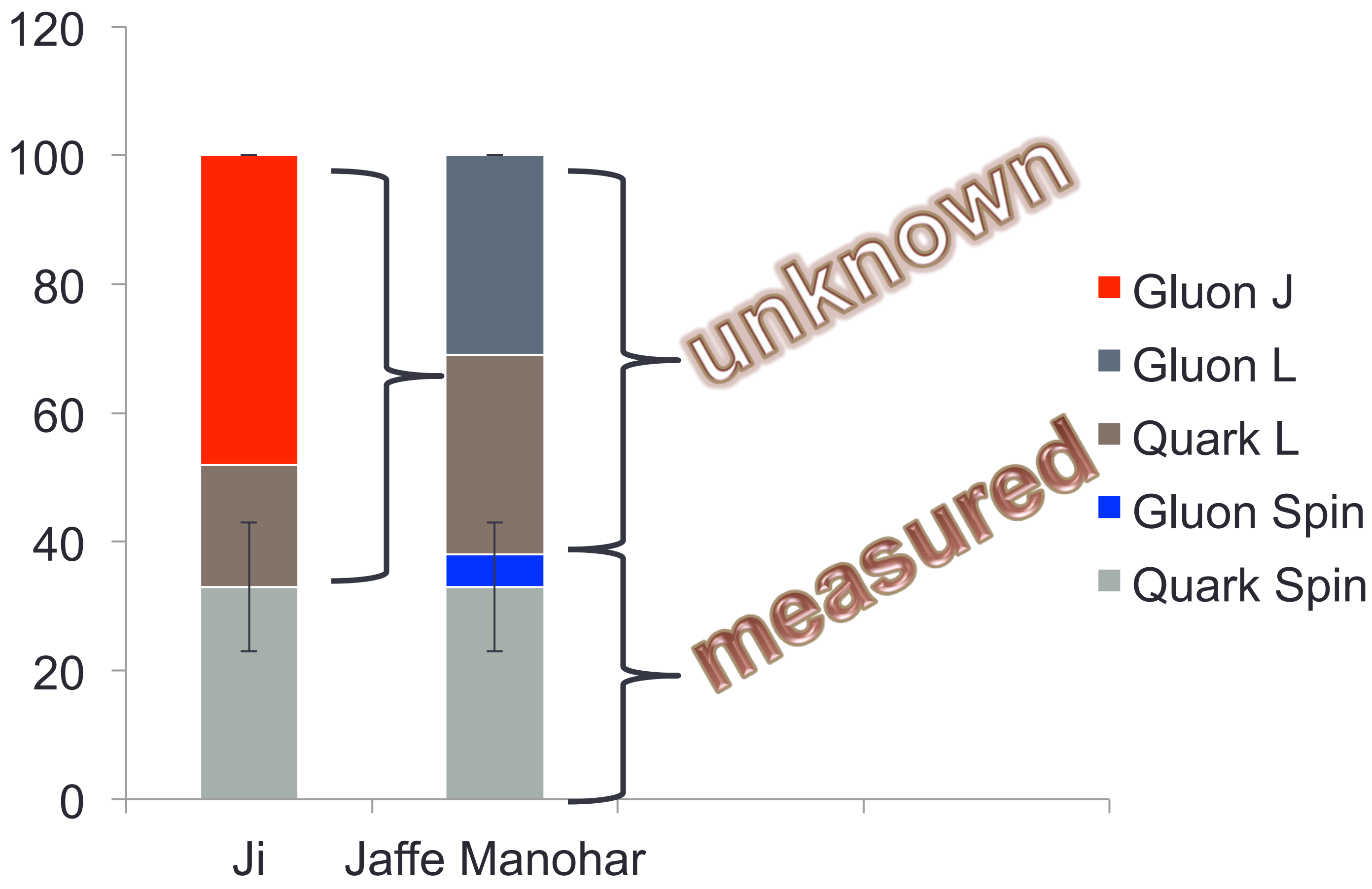




$\mathcal{L}_q \neq L_q$

$J_g \neq \mathcal{L}_g + \Delta G$

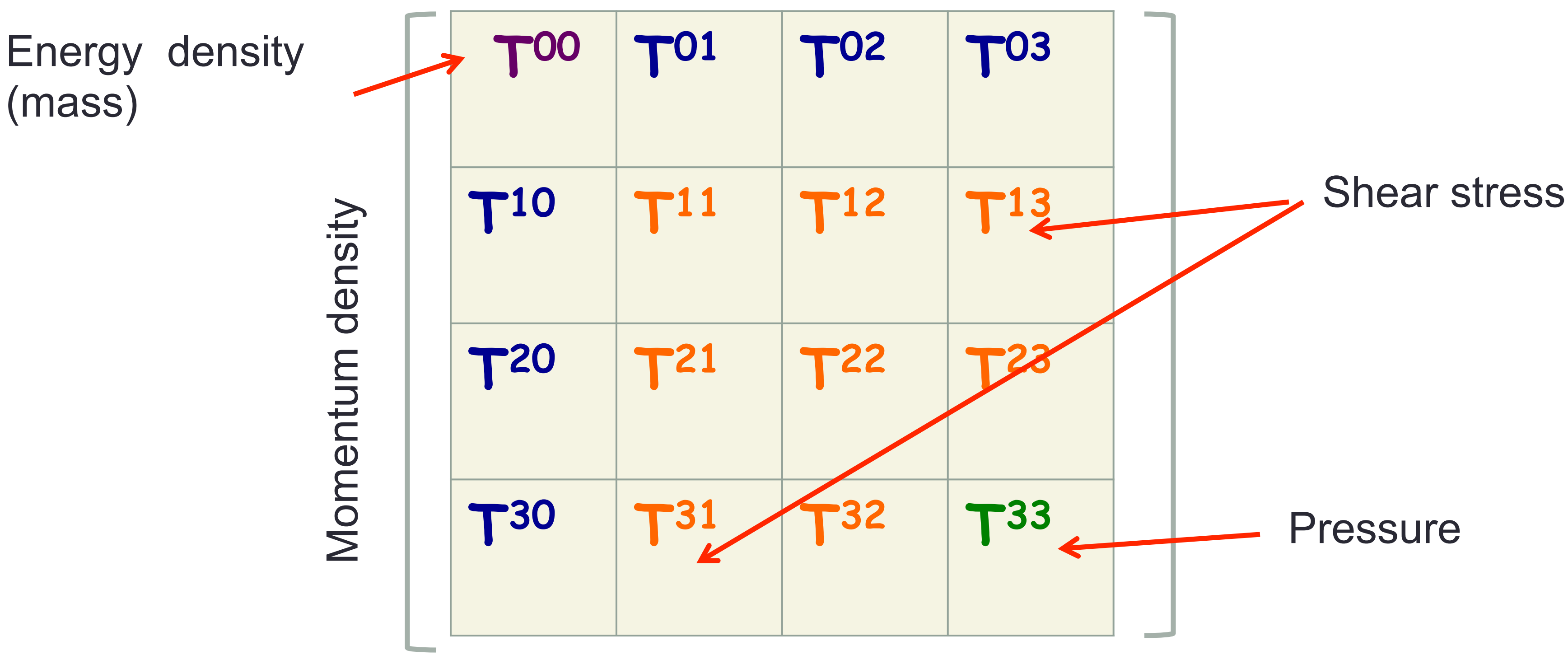
Angular Momentum Budget



The Starting Point

Jaffe and Manohar's field theoretical description of the quark and gluon orbital angular momentum through its relation to the QCD Energy Momentum Tensor.

$T^{\mu\nu}$ → $$M^{\mu\nu\lambda} = x^{\nu} T^{\mu\lambda} - x^{\lambda} T^{\mu\nu}$$ Angular Momentum density



$$T^{\mu\nu} = \frac{1}{4} i q \bar{\psi} \left(\gamma^{\mu} \overleftrightarrow{D}^{\nu} + \gamma^{\nu} \overleftrightarrow{D}^{\mu} \right) \psi + Tr \left\{ F^{\mu\alpha} F^{\nu}_{\alpha} - \frac{1}{2} g^{\mu\nu} F^{2} \right\}$$

Jaffe Manohar: *

$$M^{+12} = \psi^{\dagger}\sigma^{12}\psi + \psi^{\dagger}\left[\vec{x}\times(-i\partial)\right]^{3}\psi + Tr(\varepsilon^{+-ij}F^{+j}A^{j}) + 2iTrF^{+j}(\vec{x}\times\partial)A^{j}$$

$\Delta\Sigma$ $\mathcal{L}_q$ ΔG $\mathcal{L}_g$

Ji:

$$M^{+12} = \psi^{\dagger}\sigma^{12}\psi + \psi^{\dagger}\left[\vec{x}\times\left(-i\vec{D}\right)\right]^{3}\psi + \left[\vec{x}\times\left(\vec{E}\times\vec{B}\right)\right]^{3}$$

$\Delta\Sigma$ L_q J_g

J_q (= $\Delta\Sigma$ + L_q)

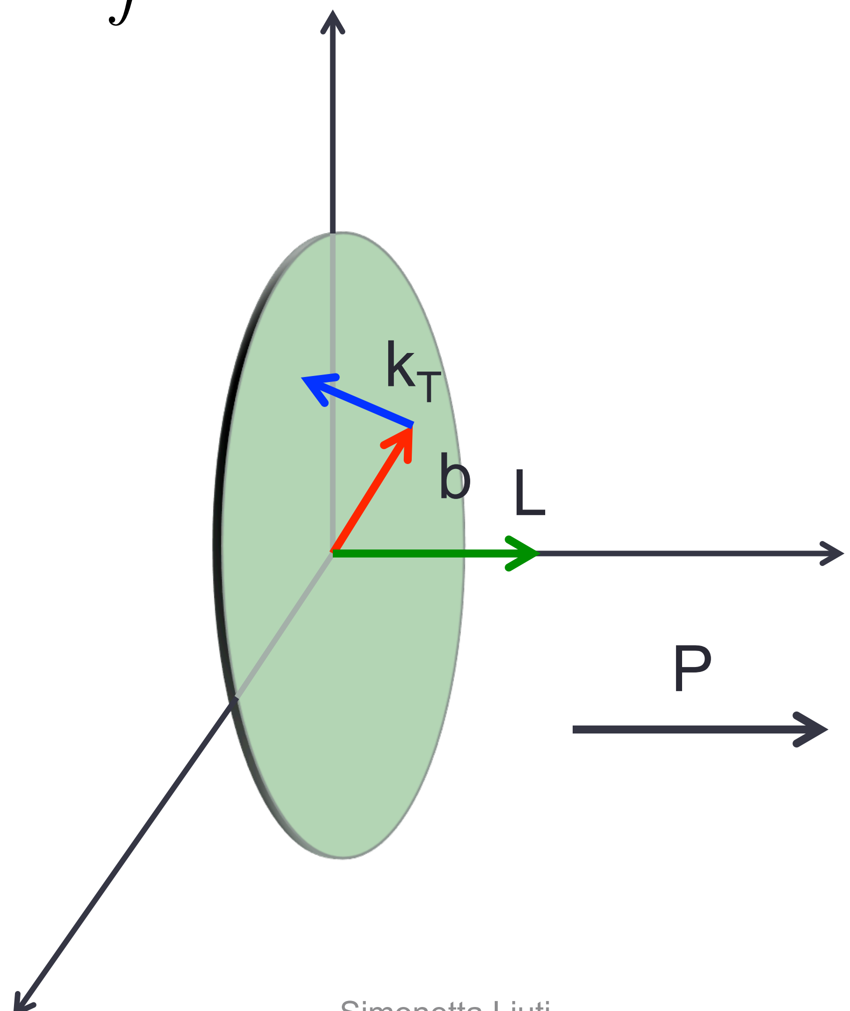
*Chen, Goldman et al., are consistent with this definition (see K.F.Liu et al.)

The first step towards an observable effect…

Partonic OAM: Wigner Distributions

$$L_q^{\mathcal{U}} = \int dx \int d^2\mathbf{k}_T \int d^2\mathbf{b}\,(\mathbf{b} \times \mathbf{k}_T)_z\,\mathcal{W}^{\mathcal{U}}(x, \mathbf{k}_T, \mathbf{b})$$

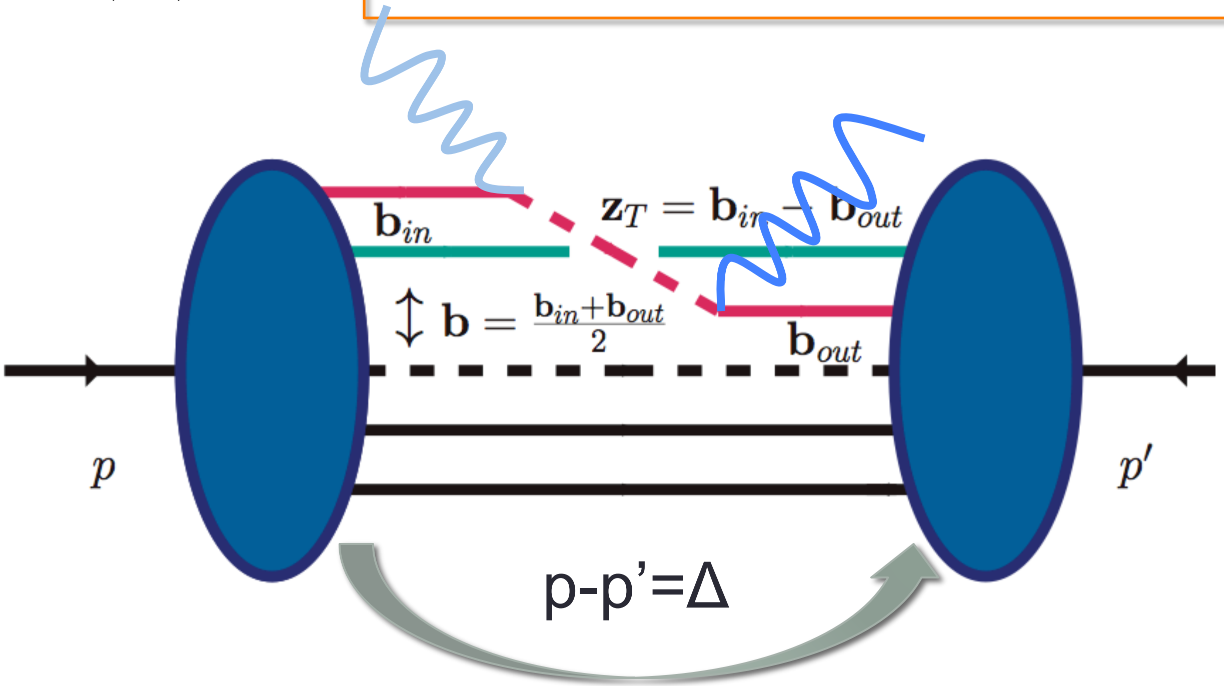
Hatta
Lorce, Pasquini,
Xiong, Yuan



Wigner Distribution

$$\mathcal{W}^{\mathcal{U}} = \frac{1}{2}\int \frac{d^2\mathbf{\Delta}_T}{(2\pi)^2} e^{i\Delta_T\cdot b} \int dz^- d^2\mathbf{z}_T\, e^{ikz} \langle P-\Delta, \Lambda' \mid \bar{q}(0)\gamma^+\mathcal{U}(0,z)q(z) \mid P, \Lambda\rangle \,|_{z^+=0}$$

GTMD



- Δ_T Fourier conjugate: **b** = transverse position of the quark inside the proton
- k_T Fourier conjugate: $\mathbf{z}_T$= transverse distance traveled by the struck quark between the initial and final scattering

Which GTMD?

The quark-quark correlator for a spin ½ hadron has been parametrized up to twist four in terms of GTMDs, TMDs and GPDs, in a complete way in:

Generalized parton correlation functions for a spin-1/2 hadron

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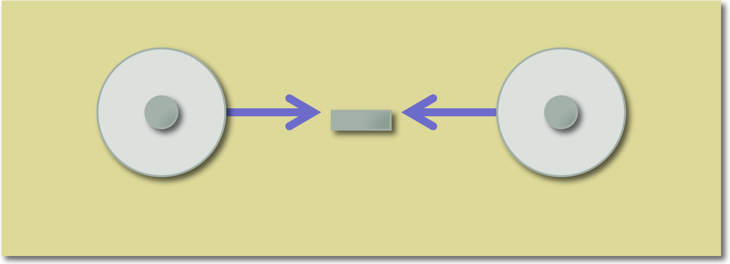
JHEP08(2009)

F_{14}

$$W^{\gamma^+}_{\Lambda\Lambda'} = \frac{1}{2P^+}\overline{U}(p',\Lambda')\left[\gamma^+ F_{11} + \frac{i\sigma^{i+}\Delta^i_T}{2M}(2F_{13}-F_{11}) + \frac{i\sigma^{i+}\bar{k}^i_T}{2M}(2F_{12}) + \frac{i\sigma^{ij}\bar{k}^i_T\Delta^j_T}{M^2}F_{14}\right]U(p,\Lambda)$$

$$= \delta_{\Lambda,\Lambda'}F_{11} + \delta_{\Lambda,-\Lambda'}\frac{-\Lambda\Delta_1 - i\Delta_2}{2M}(2F_{13}-F_{11}) + \delta_{\Lambda,-\Lambda'}\frac{-\Lambda\bar{k}_1 - i\bar{k}_2}{2M}(2F_{12}) + \delta_{\Lambda,\Lambda'}i\Lambda\frac{\bar{k}_1\Delta_2 - \bar{k}_2\Delta_1}{M^2}F_{14}$$

helicity non-flip



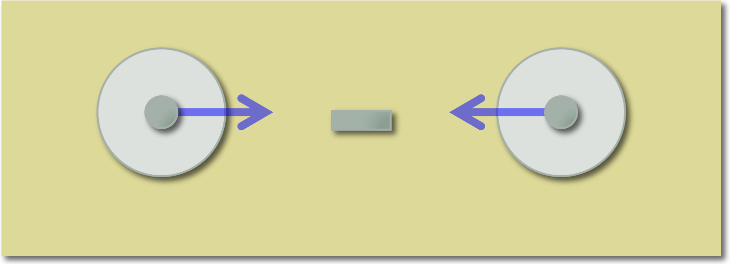
UL correlation: unpolarized quark density in a longitudinally polarized proton

G_{11} $(L \cdot S) \to \frac{1}{2}\int d^2\mathbf{b}\,(\mathbf{b}\times\mathbf{k}_T)_z\,\langle \bar{q}(0)\gamma^+\gamma_5 q(z)\rangle$

$$W^{\gamma^+\gamma_5}_{\Lambda\Lambda'} = \frac{1}{2M}\overline{U}(p',\Lambda')\left[-\frac{i\epsilon^{ij}_T k^i_T \Delta^j_T}{M^2}G_{11} + \frac{i\sigma^{i+}\gamma^5 k^i_T}{P^+}G_{12} + \frac{i\sigma^{i+}\gamma^5\Delta^i_T}{P^+}G_{13} + i\sigma^{+-}\gamma^5 G_{14}\right]U(p,\Lambda)$$

$$= \left[-\frac{i(k_1\Delta_2 - k_2\Delta_1)}{M^2}G_{11} + \Lambda G_{14}\right]\delta_{\Lambda\Lambda'} + \left[\frac{\Delta_1 + i\Lambda\Delta_2}{M}\left(G_{13} + \frac{i\Lambda(k_1\Delta_2 - k_2\Delta_1)}{2M^2}G_{11}\right) + \frac{k_1 + i\Lambda k_2}{M}G_{12}\right]\delta_{-\Lambda,\Lambda'}$$

helicity non-flip



UL correlation: longitudinally polarized quark density in an unpolarized proton

Integral relations

$$L_q = -\int_0^1 dx \int d^2k_T \, \frac{k_T^2}{M^2} \, F_{14} = -\int_0^1 dx \, F_{14}^{(1)}$$

$$L_q \cdot S_q = -\int_0^1 dx \int d^2k_T \, \frac{k_T^2}{M^2} \, G_{11} = -\int_0^1 dx \, G_{11}^{(1)}$$

Lorce, Pasquini, Xiong, Yuan
Hatta, Yoshida
Ji, Xiong, Yuan

2. LIR

Lorentz Invariance Relations (LIR)

(see D. Pitonyak and A. Rajan's talks)

- LIR in the off-forward sector: relations between twist-3 GPDs (➔PDFs) and k_T moments of GTMDs (➔TMDs)
- Based on the most general Lorentz invariant decomposition of the fully unintegrated quark-quark correlator
- LIRs are a consequence of there being a smaller number of independent unintegrated terms in the decomposition than the number of GTMDs

$$\Phi^{U} = \int \frac{d^4 z}{(2\pi)^4} e^{i(k\cdot z)} \langle P',\Lambda' | \bar{\psi}(0)\gamma^{+}\mathcal{U}(0,\infty | n)\psi(z) | P,\Lambda\rangle$$

➔ parametrized in terms of invariant functions A_1, A_2, …

(Meissner, Metz and Schlegel (2009), Mulders, Tangerman, Pijlman, Bacchetta….)

$$\tilde{\Phi}^{U} = \int dk^{-} \Phi^{U}$$

➔ parametrized in terms of invariant functions F_{11}, F_{12}, …, F_{21}, F_{22}…

Specifically, one finds the following relations (A. Rajan's talk)

tw 2

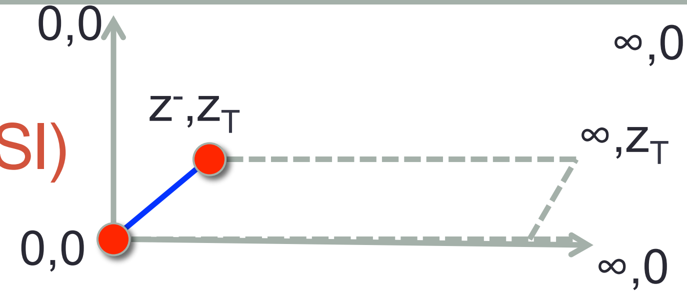
$$\frac{k_T\cdot\Delta_T}{\Delta_T^2}F_{12} + F_{13} = 2P^{+}\int dk^{-}\left(\frac{k_T\cdot\Delta_T}{\Delta_T^2}A_5 + A_6 - \frac{xP^2 - k\cdot P}{M^2}(A_8 + xA_9)\right)$$

$$F_{14} = 2P^{+}\int dk^{-}\,(A_8 + xA_9)$$

tw 3

$$\frac{k_T\cdot\Delta_T}{\Delta_T^2}F_{27} + F_{28} = 2P^{+}\int dk^{-}\left(\frac{k_T\cdot\Delta_T}{\Delta_T^2}A_5 + A_6 + \frac{1}{M^2}\left(\frac{(k_T\cdot\Delta_T)^2}{\Delta_T^2} - k_T^2\right)A_9\right)$$

Generalized LIR for straight gauge link (no FSI)



Obtained by studying in detail the k_T structure of GTMDs and twist 3 GPDs for a straight gauge link (Ji's definition)

$L_q(x)$

OAM is given by a twist 3 GPD

$$\frac{d}{dx}\int d^2k_T\,\frac{k_T^2}{M^2}\,F_{14} = \widetilde{E}_{2T} + H + E$$

k_T moment of a GTMD

twist 3 GPD

$$\frac{d}{dx}\int d^2k_T\,\frac{k_T^2}{M^2}\,G_{11} = -\left(2\tilde{H}'_{2T} + E'_{2T} + \tilde{H}\right)$$

A. Rajan, A. Courtoy, M. Engelhardt, S.L., PRD (2016), arXiv:1601.06117

Integrating in dx one finds the OAM distribution function

$L_q(x)$ L_q

$$F_{14}^{(1)} = -\int_x^1 dy\,(\tilde{E}_{2T} + H + E) \;\Rightarrow\; -L_q = \int_0^1 dx F_{14}^{(1)} = \int_0^1 dx x G_2$$

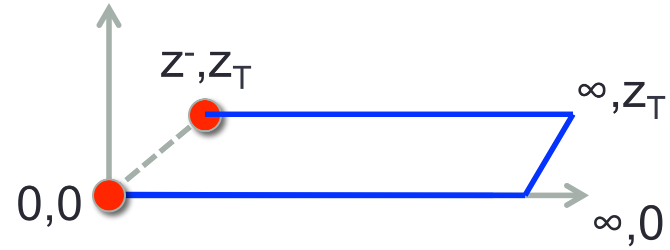
- F_{14} and $\tilde{E}_{2T}$ give us similar information on the distribution in x of OAM! new result
- In addition: we confirm and corroborate the global/integrated OAM result deducible from Ji et al

Different notation!

$$G_2 \rightarrow \tilde{E}_{2T} + H + E$$

Polyakov et al. Meissner, Metz and Schlegel, JHEP(2009)

Generalized LIR for a staple link



$$\frac{d}{dx}\int d^2k_T\,\frac{k_T^2}{M^2}\,F_{14} = \tilde{E}_{2T} + H + E + \mathcal{A}$$

LIR violating term

3. EQUATIONS OF MOTION

Equations of Motion (EoM) relation

Now insert the EoM in the correlator for a longitudinally polarized proton

$$\int \frac{dz^- d^2 z_T}{(2\pi)^3} e^{ixP^+ z^- - ik_T \cdot z_T} \langle p', \Lambda' \mid \overline{\psi}(-z/2)(\Gamma\, \mathcal{U}\, i \overrightarrow{\not{D}} + i \overleftarrow{\not{D}}\, \Gamma\, \mathcal{U})\psi(z/2) \mid p, \Lambda \rangle_{z^+=0} = 0$$

We find

$$\tilde{E}_{2T} = -\int_x^1 \frac{dy}{y}(H+E) + \left[\frac{\tilde{H}}{x} - \int_x^1 \frac{dy}{y^2}\tilde{H}\right] + \left[\frac{1}{x}\mathcal{M}_{F_{14}} - \int_x^1 \frac{dy}{y^2}\mathcal{M}_{F_{14}}\right]$$

$\int_0^1 dx \ldots$ relates to

L = J - S + 0

Consistent with OPE based relation

Polyakov et al.(2000), Hatta(2012)

$$\int_0^1 dx\, x G_2 = -\frac{1}{2}\int_0^1 dx\, x(H+E) + \frac{1}{2}\int_0^1 dx\, \tilde{H}$$

$$J_q = L_q + \frac{1}{2}\Delta\Sigma_q$$

A generalized Wandzura Wilczeck relation obtained using OPE for twist 2 and twist 3 operators for the off-forward matrix elements

Validation of Ji's Sum Rule: $J_q = L_q + \frac{1}{2}\Delta\Sigma_q$ through three independently measured quantities

u-d

A. Rajan et al, PRD (2016) arXiv:1601.06117

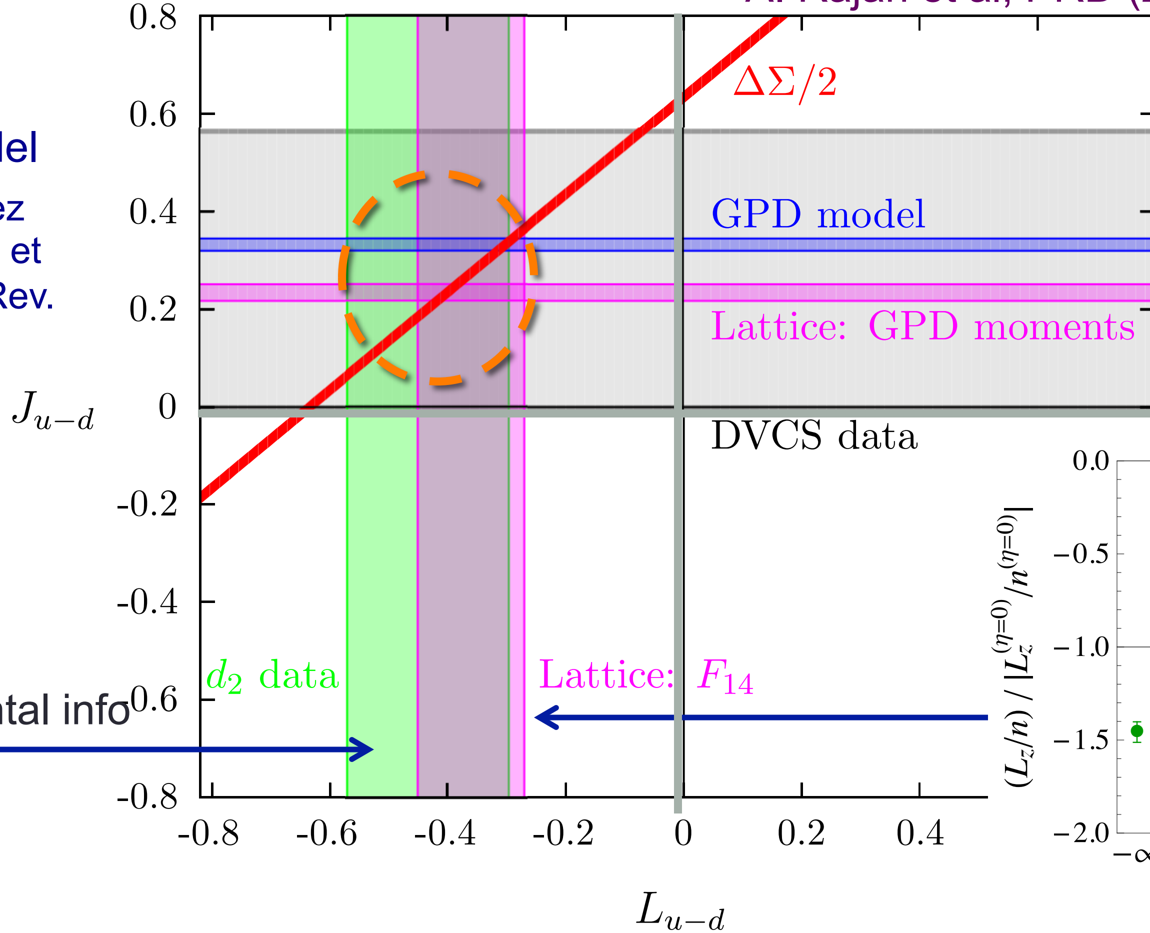
GPD model

O. Gonzalez Hernandez et al., Phys. Rev. C88; arXiv: 1206.1876

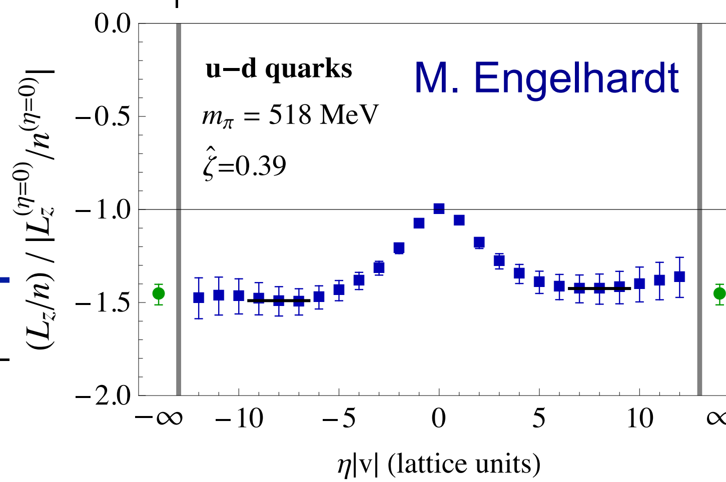
JLAB, Mazous et al. PRL (2007)

DVCS + VGG

Experimental info

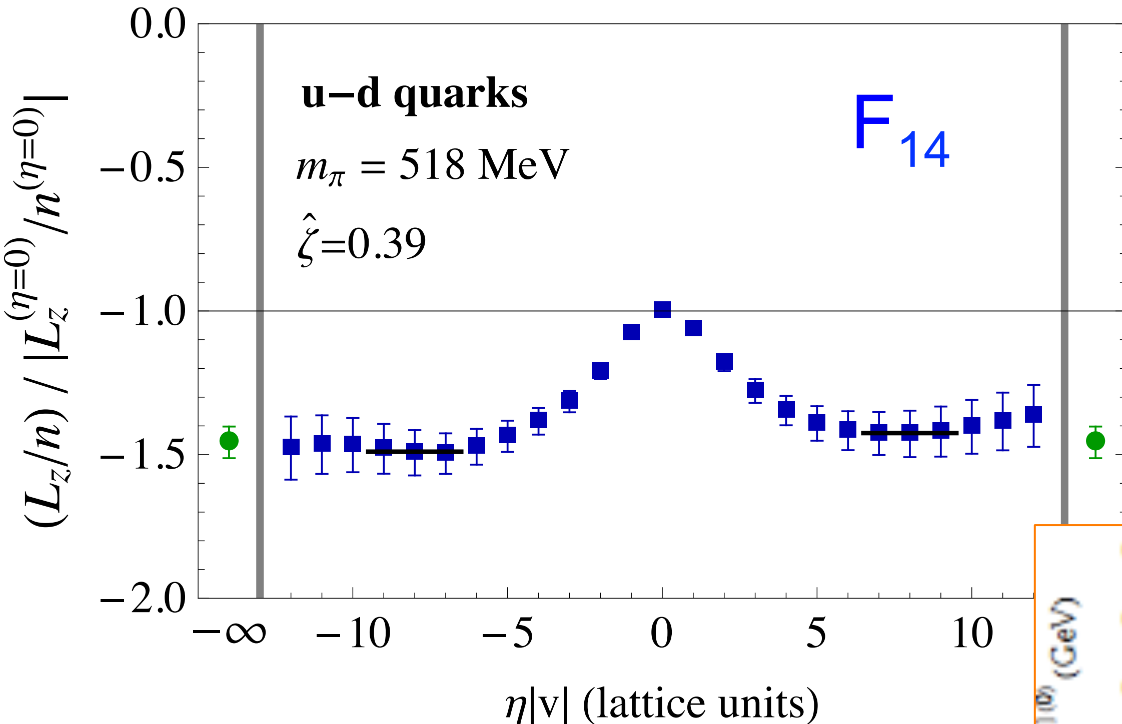


arXiv:1701.01536

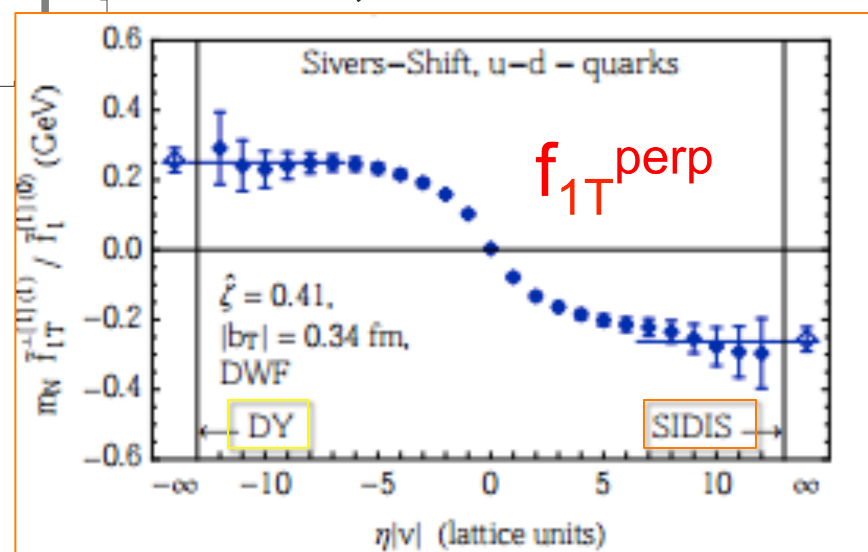


4. A PROBE OF QCD AT THE AMPLITUDE LEVEL

large effect from lattice (M. Engelhardt, arXiv:1701.01536)



PRD, arXiv:1111.4249



insight into non-perturbative aspects of QCD associated with dynamical chiral symmetry breaking

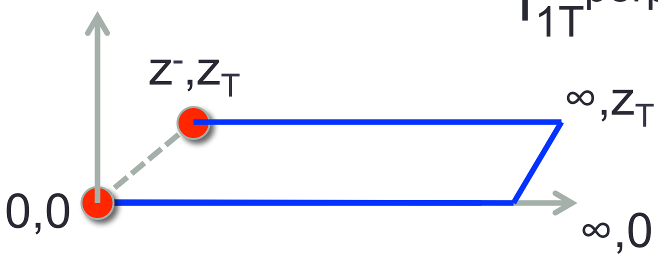
PT transformation

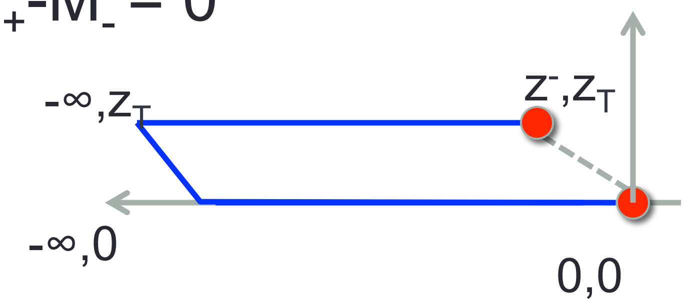
Forward case: Sivers function (J. Collins, 2002)

PT: $\langle P, S \mid \bar{\psi}(0)\gamma^{+}\psi(z) \mid P, S\rangle = \langle P, -S \mid \bar{\psi}(0)\gamma^{+}\psi(z) \mid P, -S\rangle$

M_+ $\qquad$ M_-

$f_{1T}^{perp} = M_+ - M_- = 0$





PT:

$$\langle P, S \mid \bar{\psi}(0)\gamma^{+}U(v, z)\psi(z) \mid P, S\rangle = \langle P, -S \mid \bar{\psi}(0)\gamma^{+}U(-v, z)\psi(z) \mid P, -S\rangle$$

$M_+^{v} - M_-^{-v} = 0$ ⟹ $f_{1T}^{perp,SIDIS} = M_+^{v} - M_-^{v} = -f_{1T}^{perp,DY} = M_+^{-v} - M_-^{-v}$

Off forward case: F_{14}

PT:

$$\langle P-\Delta, S \mid \bar{\psi}(0)\gamma^{+}U(v,z)\psi(z) \mid P, S\rangle = \langle P, -S \mid \bar{\psi}(0)\gamma^{+}U(-v,z)\psi(z) \mid P-\Delta, -S\rangle$$

$L_{+}^{v,\Delta}$ $\qquad$ $L_{-}^{-v,-\Delta}$

$L_{+}^{v,\Delta} - L_{-}^{-v,-\Delta} = 0$

$(k_T x \Delta_T)\ F_{14}^{\text{"SIDIS"}} = L_{+}^{v,\Delta} - L_{-}^{v,\Delta} = (k_T x \Delta_T)\ F_{14}^{\text{"DY"}} = L_{+}^{-v,\Delta} - L\_\_^{v,\Delta}$

Genuine/intrinsic twist three term in Equation of Motion relation

$$\mathcal{M}^i_{\Lambda\Lambda'} = \frac{1}{4}\int \frac{dz^- d^2 z_T}{(2\pi)^3} e^{ixP^+ z^- - ik_T\cdot z_T}$$

$$\langle p', \Lambda' \mid \overline{\psi}(-z/2) \left[(\overrightarrow{\not\partial} - ig\not A)\mathcal{U}\Gamma\Big|_{-z/2} + \Gamma\mathcal{U}(\overleftarrow{\not\partial} + ig\not A)\Big|_{z/2} \right] \psi(z/2) \mid p, \Lambda\rangle_{z^+=0}$$

$$-x\tilde{E}_{2T} = \tilde{H} - \int d^2 k_T \frac{k_T^2}{M^2} F_{14}^{\text{staple}} + \mathcal{M}_{F_{14}}^{\text{staple}}$$

$$-x\tilde{E}_{2T} = \tilde{H} - \int d^2 k_T \frac{k_T^2}{M^2} F_{14}^{\text{straight}} + \mathcal{M}_{F_{14}}^{\text{straight}}$$

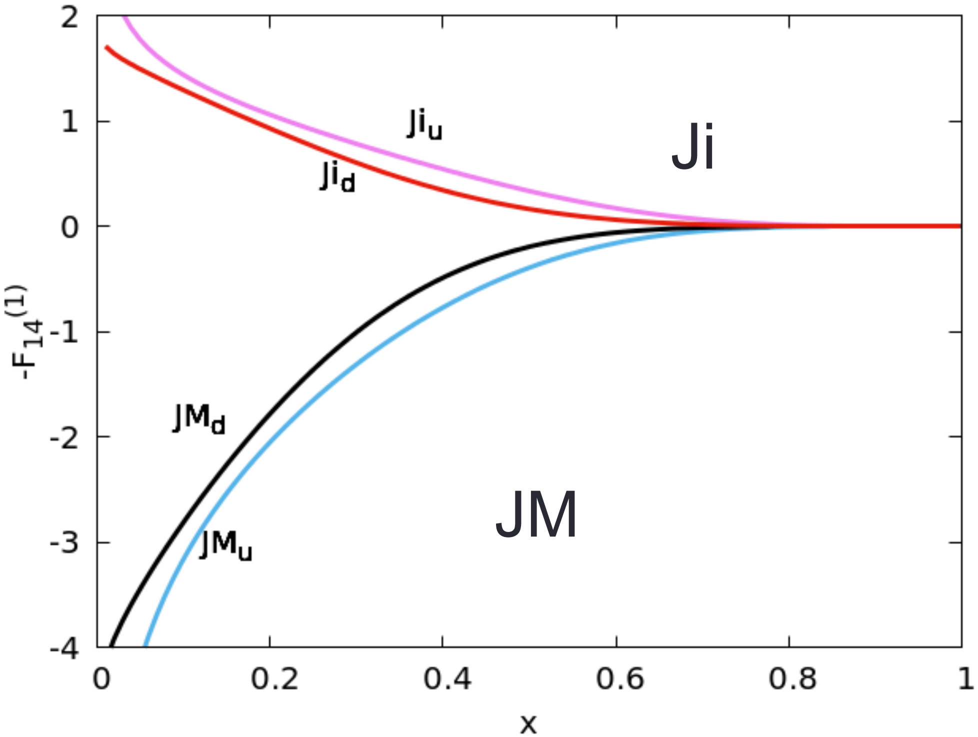
$$\mathcal{A} = \frac{d}{dx}\left(\mathcal{M}^{\text{staple}} - \mathcal{M}^{\text{straight}}\right)$$

LIR violating term

Generalized Qiu Sterman term

$$\int d^2k_T\,\frac{k_T^2}{M^2}\,F_{14}^{JM} - \int d^2k_T\,\frac{k_T^2}{M^2}\,F_{14}^{Ji} = T_F(x,x,\Delta)$$

$F_{14}^{(1)}$



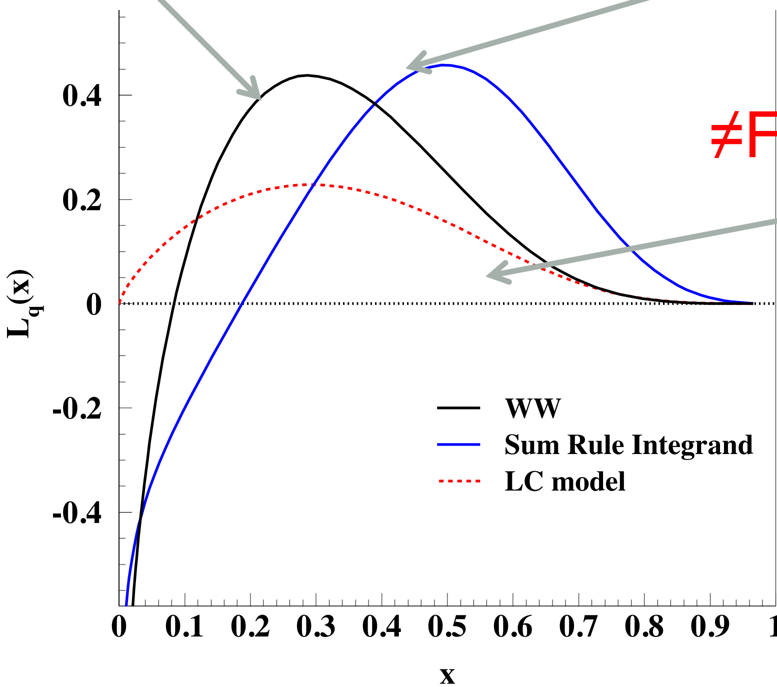
with B. Kriesten and A. Rajan, using diquark model

Ratio L_{Ji}/L_{JM}=0.72

Lattice Ratio L_{Ji}/L_{JM}=0.62±0.16(stat) (extrapolated at $\zeta=\infty$)

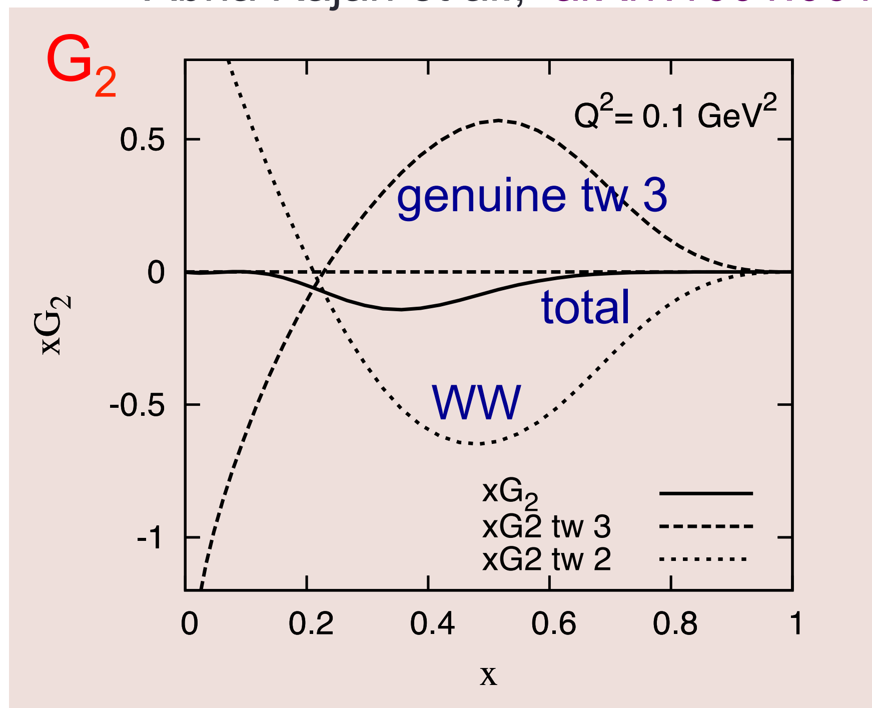
$$L_q(x,0,0) = x\int_x^1 \frac{dy}{y}(H_q(y,0,0)+E_q(y,0,0)) - x\int_x^1 \frac{dy}{y^2}\tilde{H}_q(y,0,0),$$

Low x!

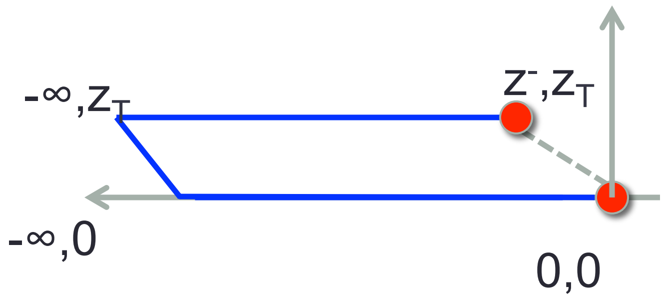


$\neq F_{14}$!

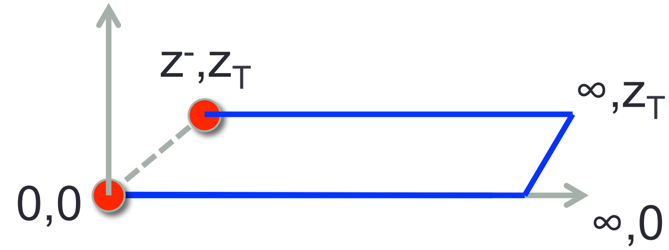
Abha Rajan et al., arXiv:1601.06117



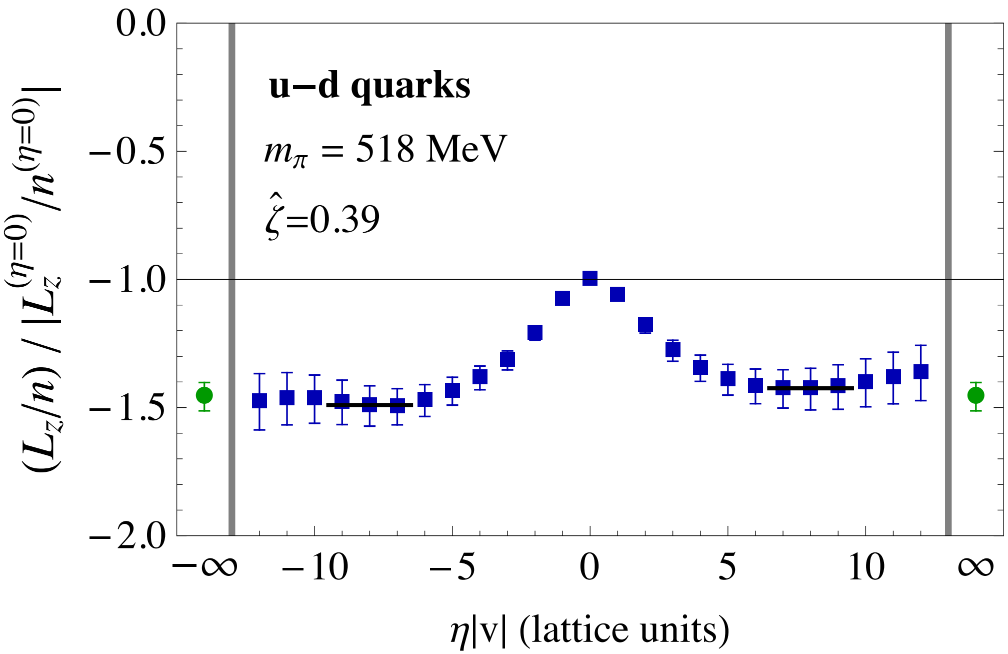
5. PROCESS DEPENDENCE



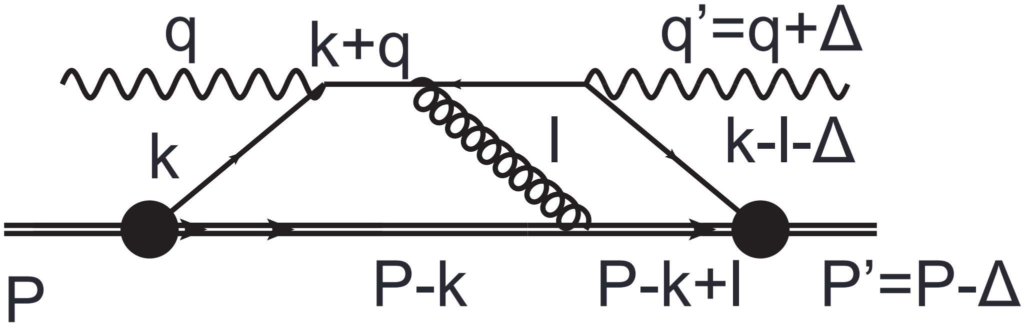
-∞,zT
z-,zT
∞,0
-∞,0
0,0



z-,zT
∞,zT
0,0
∞,0

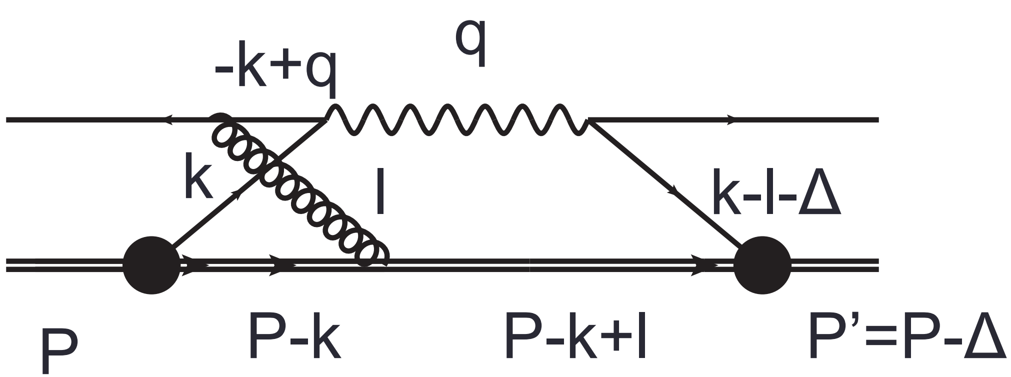


u−d quarks
m_π = 518 MeV
$\hat{\zeta}$=0.39
$(L_z/n)\,/\,|L_z^{(\eta=0)}/n^{(\eta=0)}|$
$\eta|v|$ (lattice units)
0.0
−0.5
−1.0
−1.5
−2.0
−∞
−10
−5
0
5
10
∞



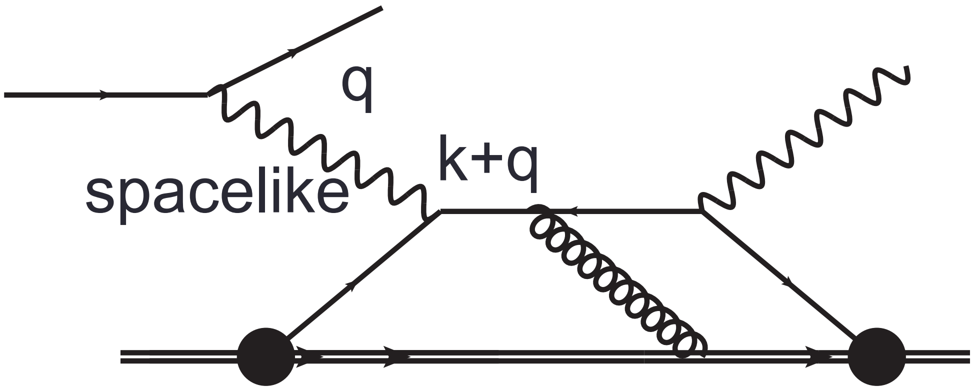
“SIDIS-like”

$$F_{1,4} = \int \frac{d^2 l}{(2\pi)^2} \frac{e_c^2 g_s^2 M^2 2P^+ (1-x)^2 \left(1 + \frac{l_T}{k_T}\cos\phi_l\right)}{2x(l_T^2 + m_g^2)((k-l)^2 - M_\Lambda^2)^2((k-\Delta)^2 - M_\Lambda^2)^2}$$

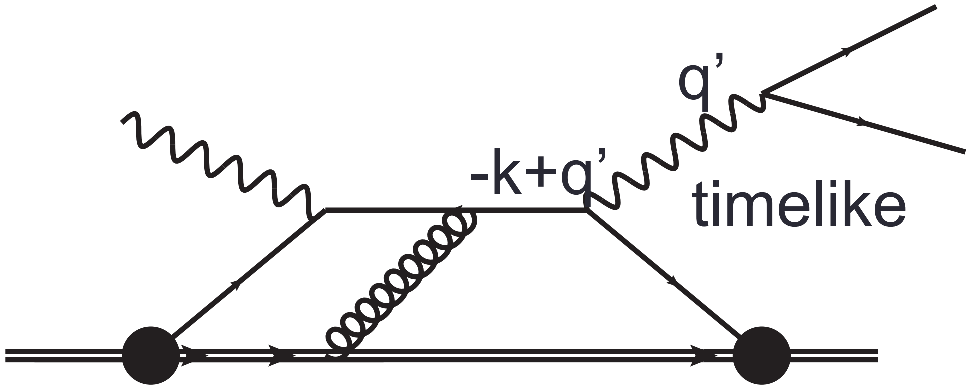


“DrellYan-like”

Two additional processes: DVCS and TCS twist three contributions



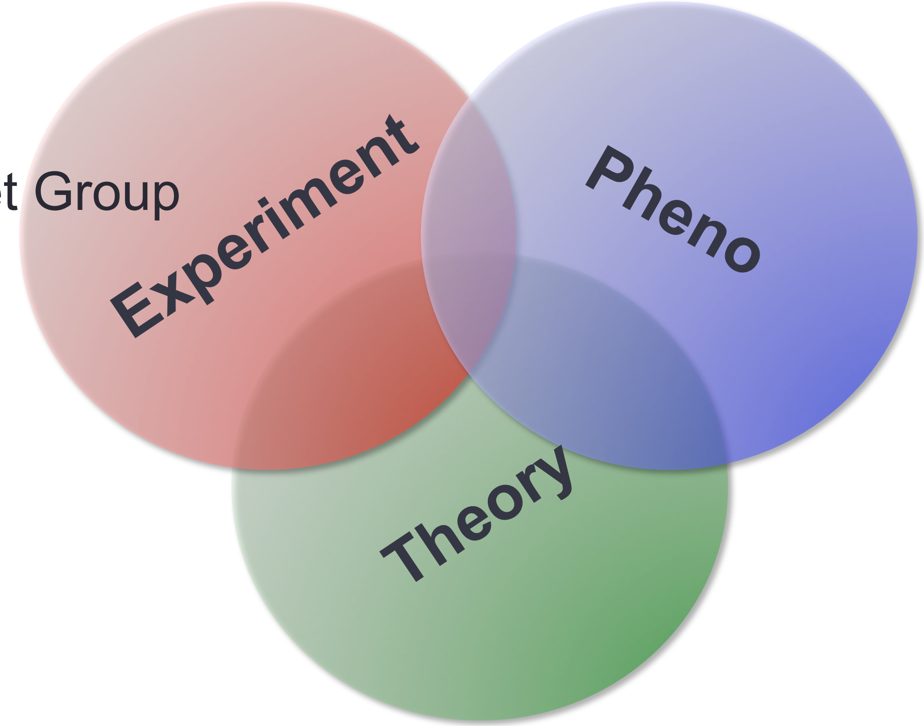
DVCS



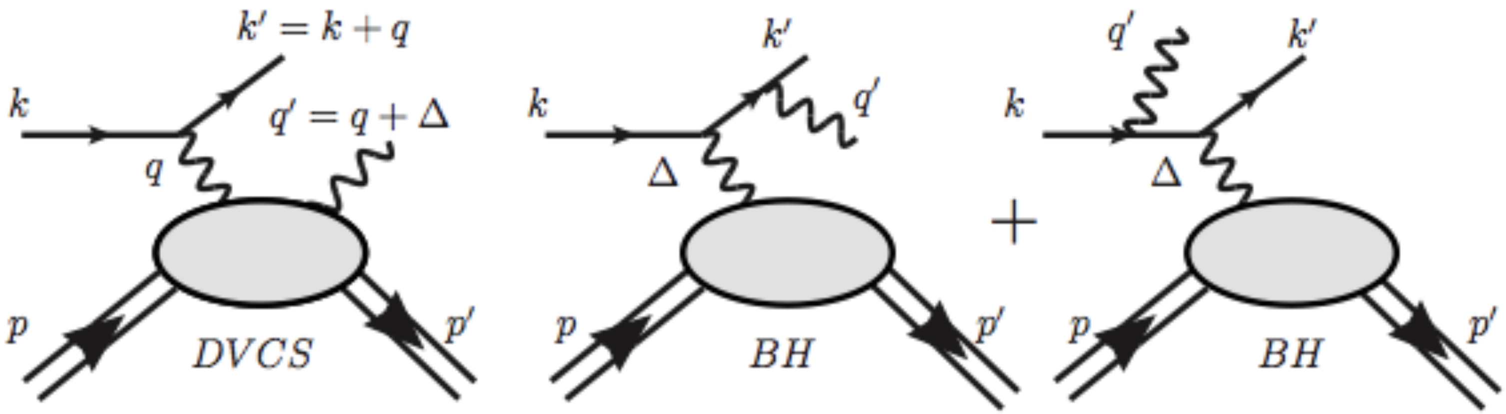
TCS

Extracting twist 3 GPDs from these processes will allow us to zoom into aspects of the "sign change"

Dustin Keller & U.Va. Polarized Target Group



Deeply Virtual Exclusive Photoproduction



$$\frac{d^5\sigma}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = \frac{\alpha^3}{16\pi^2(s-M^2)^2\sqrt{1+\gamma^2}}\left|T\right|^2 ,$$

$$T(k,p,k',q',p') = T_{DVCS}(k,p,k',q',p') + T_{BH}(k,p,k',q',p'),$$

BASIC MODULE (based on helicity amplitudes)

$$\sum_{\Lambda'_\gamma,\,\Lambda'} \left(T^{h\Lambda'_\gamma}_{DVCS,\Lambda\Lambda'}\right)^* T^{h\Lambda'_\gamma}_{DVCS,\Lambda\Lambda'} =$$

$$\frac{1}{Q^2}\frac{1}{1-\epsilon}\Big\{(F^{11}_{\Lambda+} + F^{11}_{\Lambda-} + F^{-1-1}_{\Lambda+} + F^{-1-1}_{\Lambda-}) + \epsilon(F^{00}_{\Lambda+} + F^{00}_{\Lambda-})$$

$$+2\sqrt{\epsilon(1+\epsilon)}\,\mathrm{Re}\,(-F^{01}_{\Lambda+} - F^{01}_{\Lambda-} + F^{0-1}_{\Lambda+} + F^{0-1}_{\Lambda-}) + 2\epsilon\,\mathrm{Re}\,(F^{1-1}_{\Lambda+} + F^{1-1}_{\Lambda-})$$

$$+(2h)\Big[\sqrt{1-\epsilon^2}\,(F^{11}_{\Lambda+} + F^{11}_{\Lambda-} - F^{-1-1}_{\Lambda+} - F^{-1-1}_{\Lambda-})$$

polarized lepton

$$-\ 2\sqrt{\epsilon(1-\epsilon)}\,\mathrm{Re}\,(F^{01}_{\Lambda+} + F^{01}_{\Lambda-} + F^{0-1}_{\Lambda+} + F^{0-1}_{\Lambda-})\Big]\Big\}$$

Helicity amplitudes

Virtual Photon helicities

$$F_{\Lambda\Lambda'}^{\Lambda_{\gamma^*}^{(1)}\Lambda_{\gamma^*}^{(2)}} = \sum_{\Lambda_{\gamma'}} \left(f_{\Lambda\Lambda'}^{\Lambda_{\gamma^*}^{(1)}\Lambda_{\gamma'}} \right)^* f_{\Lambda\Lambda'}^{\Lambda_{\gamma^*}^{(2)}\Lambda_{\gamma'}}$$

Initial and final proton helicities

$$F^{11}_{++} = (1-\xi^2) \mid \mathcal{H} + \widetilde{\mathcal{H}} \mid^2 - \xi^2 \left[(\mathcal{H}^* + \widetilde{\mathcal{H}})^* (\mathcal{E} + \widetilde{\mathcal{E}}) + (\mathcal{H} + \widetilde{\mathcal{H}})(\mathcal{E}^* + \widetilde{\mathcal{E}}^*) \right]$$

$$F^{11}_{--} = (1-\xi^2) \mid \mathcal{H} - \widetilde{\mathcal{H}} \mid^2 - \xi^2 \left[(\mathcal{H}^* - \widetilde{\mathcal{H}})^* (\mathcal{E} - \widetilde{\mathcal{E}}) + (\mathcal{H} - \widetilde{\mathcal{H}})(\mathcal{E}^* - \widetilde{\mathcal{E}}^*) \right]$$

$$F^{11}_{+-} = \frac{t_0 - t}{4M^2} \mid \mathcal{E} + \xi \widetilde{\mathcal{E}} \mid^2$$

$$F^{11}_{-+} = \frac{t_0 - t}{4M^2} \mid \mathcal{E} - \xi \widetilde{\mathcal{E}} \mid^2$$

Phase dependence

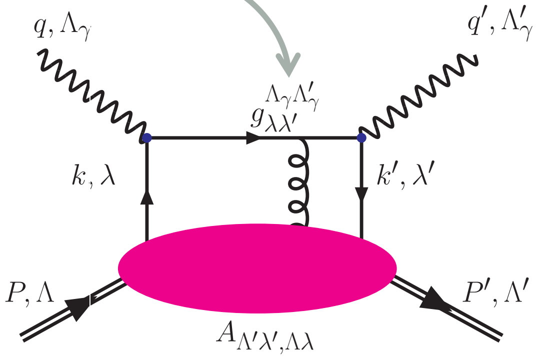
$$f \rightarrow e^{i\left[\Lambda_{\gamma*}-\Lambda_{\gamma'}-(\Lambda-\Lambda')\right]\phi}$$

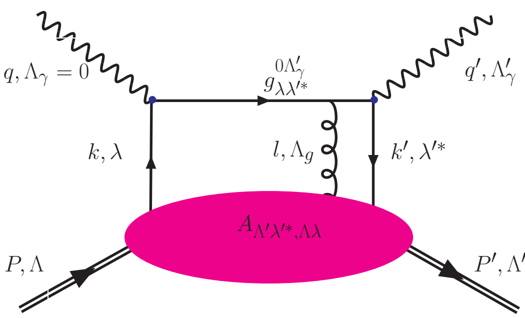
The phase is determined entirely by the virtual photon helicity which can be different for the amplitude and its conjugate

Twist 3

$$f^{01}_{\Lambda\Lambda'} = g^{01}_{-*+} \otimes A_{\Lambda'+,\Lambda-^*} + g^{01}_{-+^*} \otimes A_{\Lambda'+^*,\Lambda-} + g^{01}_{+^*-} \otimes A_{\Lambda'-,\Lambda+^*} + g^{01}_{+-^*} \otimes A_{\Lambda'-^*,\Lambda+}$$

"Bad" component (exchanged gluon flips the quark chirali





The unpolarized cross section: example

$$\sigma^{UU} = \frac{\Gamma}{Q^2(1-\epsilon)} \left[F_{UU,T} + \epsilon F_{UU,L} + \epsilon \cos 2\phi F_{UU}^{\cos 2\phi} + \sqrt{\epsilon(\epsilon+1)} \cos\phi F_{UU}^{\cos\phi} \right]$$

$$F_{UU,T} = 2(F_{++}^{11} + F_{+-}^{11} + F_{-+}^{11} + F_{--}^{11}),$$

Twist 2

$$F_{UU,L} = 2F_{++}^{00}$$

Twist 4

$$F_{UU}^{\cos\phi} = \mathrm{Re}\left[F_{++}^{01} + F_{--}^{01}\right]$$

Twist 3

$$F_{UU}^{\cos 2\phi} = \mathrm{Re}\left[F_{++}^{1-1} + F_{+-}^{1-1} + F_{-+}^{1-1} + F_{--}^{1-1}\right]$$

Photon helicity flip: transverse gluons

We connect the tw 3 amps DVCS formalism with the TMD, GPD, GTMD comprehensive parametrization in Meissner Metz and Schlegel, JHEP08 (2009)

Example

$$A_{+-,++^*} = \frac{1}{2}\left(\tilde{E}_{2T} - \overline{E}_{2T} + \tilde{E}'_{2T} + \overline{E}'_{2T}\right)$$

$$A_{+-^*,++} = \frac{1}{2}\left(-\tilde{E}_{2T} + \overline{E}_{2T} + \tilde{E}'_{2T} + \overline{E}'_{2T}\right)$$

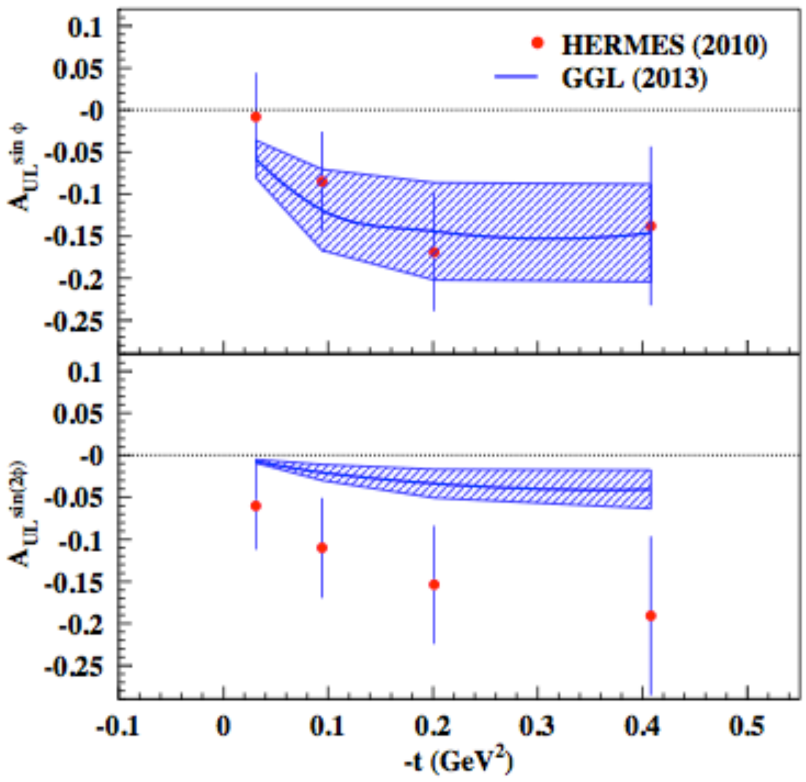
$\vdots$

Spin Orbit interaction

Orbital angular momentum

DVCS: bilinears of tw 2 and tw 3 CFFs

$$F_{++}^{01} = \mathcal{P}\left[\mathcal{H}^*(\tilde{\mathcal{E}}_{2T} - \bar{\mathcal{E}}_{2T} + \ldots), \ldots\right]$$

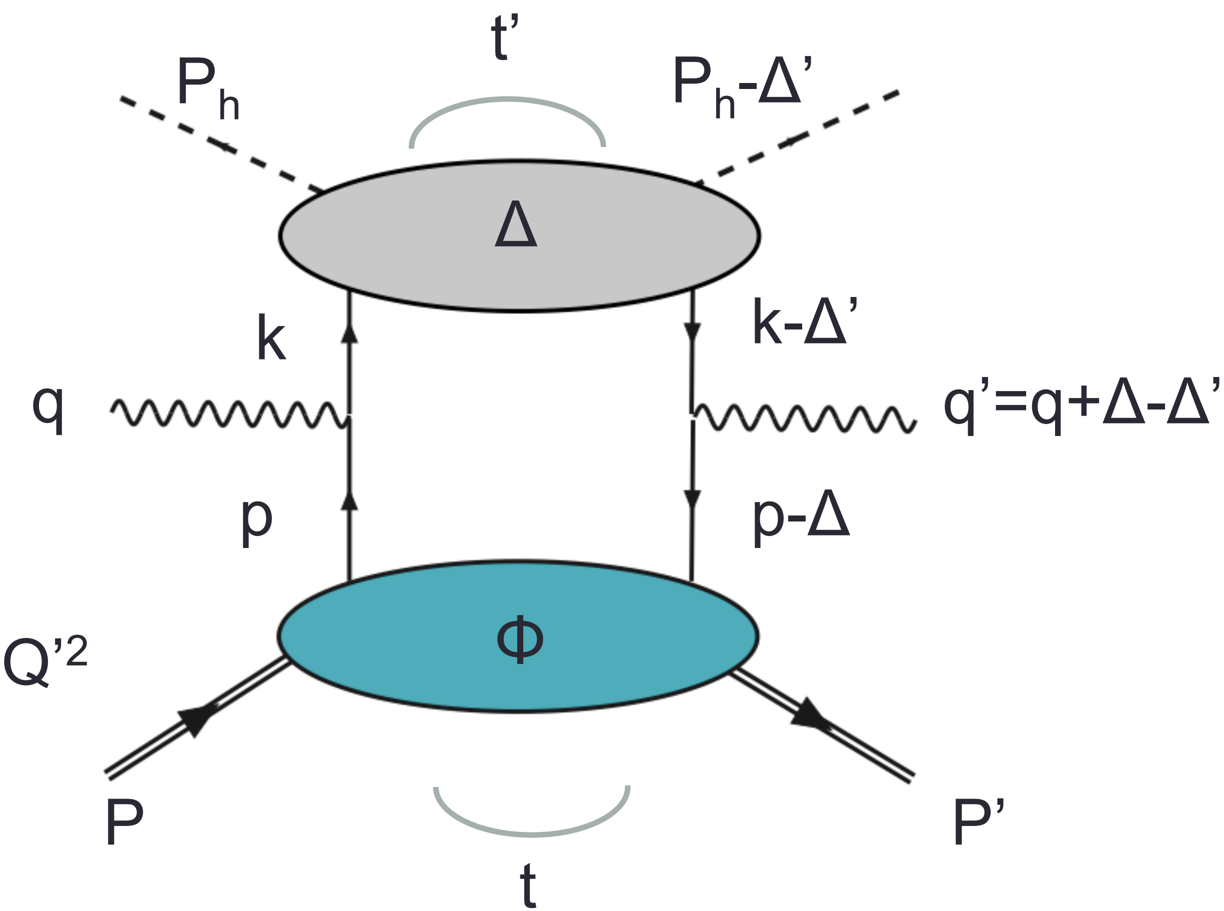


Extraction from experiment
using Wandzura Wilczek approximation

A.Courtoy, G.Goldstein, O.Gonzalez Hernandez, S.L. and A.Rajan, PLB 731(2014)

Our proposal: GTMDs from Double DVCS hadron production (off-forward SIDIS)

$$ep \to e'\pi^+\pi^-\mu^+\mu^-p'$$

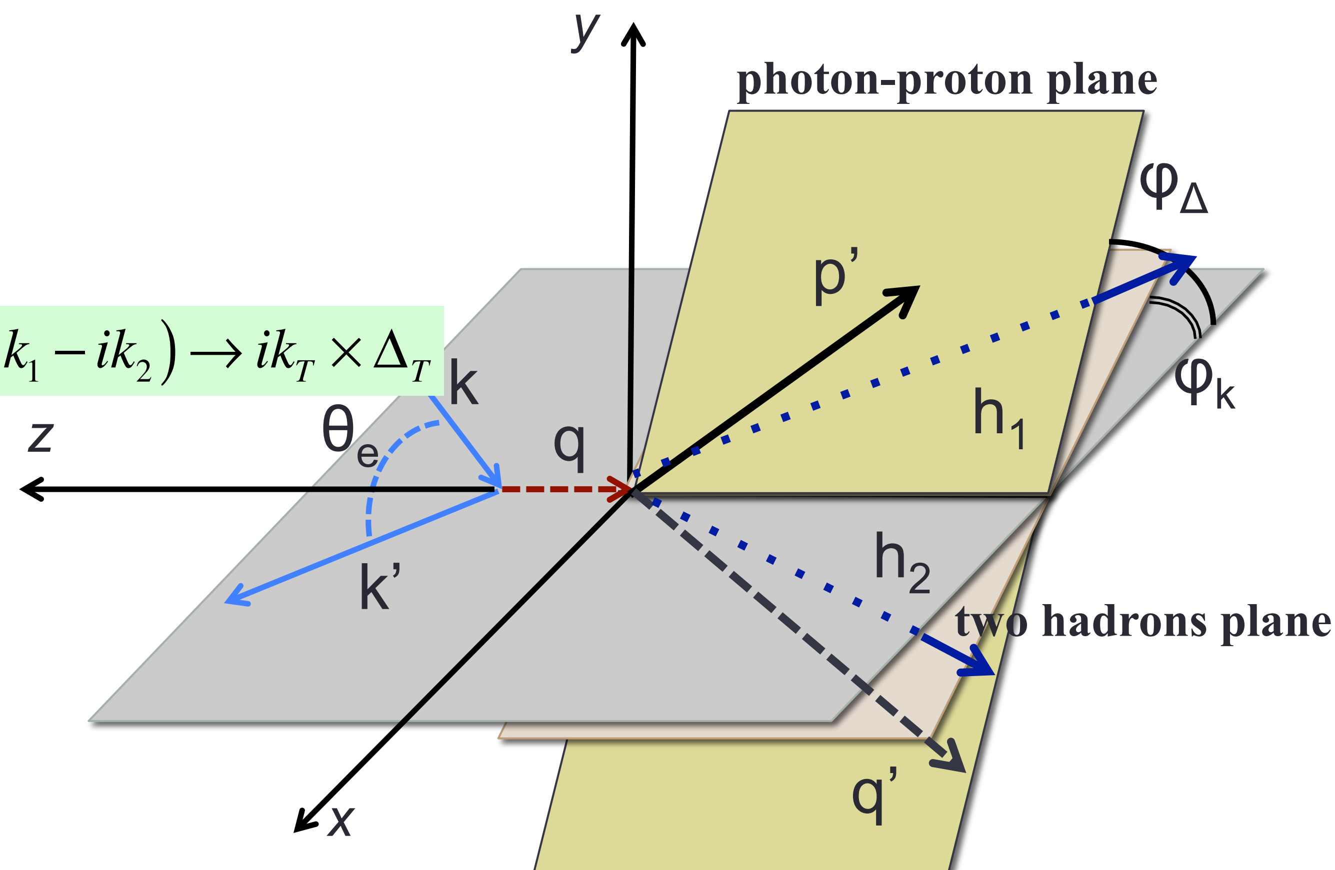


$t,t',P_h^2<Q^2,Q'^2$

Helicity amplitude formalism for DDVCS hadron production

- To measure F_{14} one has to be in a frame where the reaction cannot be viewed as a two-body quark-proton scattering
- In the CoM the amplitudes are imaginary ➔UL term goes to 0 unless one defines two hadronic planes

$$|\Delta| e^{i\varphi_\Delta} |k_T| e^{i\varphi_k} (\Delta_1 - i\Delta_2)(k_1 - ik_2) \rightarrow ik_T \times \Delta_T$$



Conclusions and Outlook

The connection we established through the new relations between (G)TMDs and Twist 3 GPDs, not only allows us to evaluate the angular momentum sum rule, it also opens many interesting avenues:

- It allows us to study in detail the role of quark-gluon correlations, in a framework where the role of k_T and off-shellness, k^2, is manifest.
- OAM was obtained so far by subtraction (also in lattice). We can now both calculate OAM on the lattice (GTMD) and validate this through measurements (twist 3 GPD)
- It provides an ideal setting to test renormalization issues, evolution etc…
- QCD studies at the amplitude level shed light on chiral symmetry breaking
- TWIST THREE GPDs ARE CRUCIAL TO STUDY QCD AT THE AMPLITUDE LEVEL

Back up

Helicity and Transverse Spin Structures of H+E

$$\left(A_{++,++}+A_{+-,+-}+A_{-+,-+}+A_{--,--}\right)+\left(A_{++,-+}+A_{+-,--}-A_{--,+-}-A_{-+,++}\right)$$

$$\left(A^X_{++,++}+A^X_{+-,+-}+A^X_{-+,-+}+A^X_{--,--}\right)+\left(A^X_{++,++}+A^X_{+-,+-}-A^X_{-+,-+}-A^X_{--,--}\right)$$

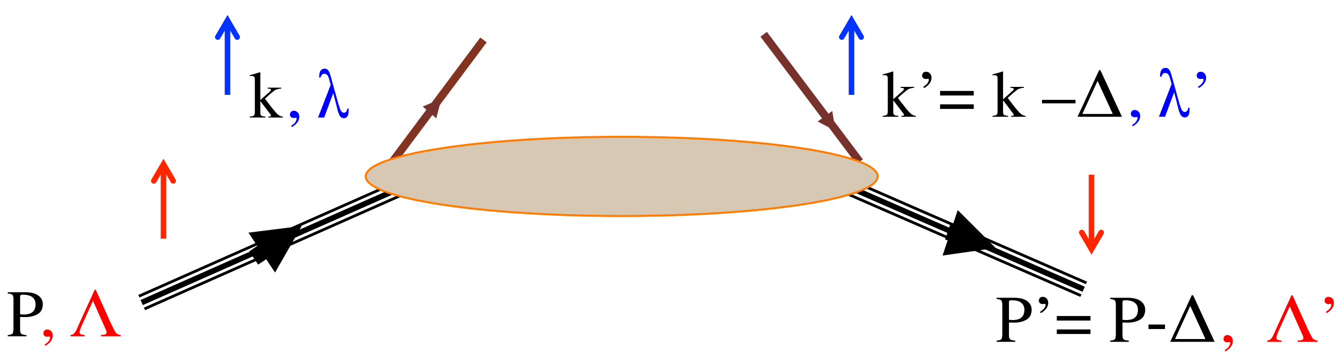
$$\approx H - i\Delta_2 E$$

= Helicity flips

Transv. spin conserved "non flip"

E measures J, not L, but a change of one unit of L (because of the helicity flip)

$$S_z = -1/2 \to 1/2 \Rightarrow \Delta L_z = 1$$ at fixed J



Brodsky and Drell '80s, Belitsky, Ji and Yuan, '90's