DVCS & TCS IN NEW HELICITY AMPLITUDES FORMALISM

HIGH INTENSITY PHOTON SOURCE WORKSHOP CUA, FEBRUARY 6-7, 2017

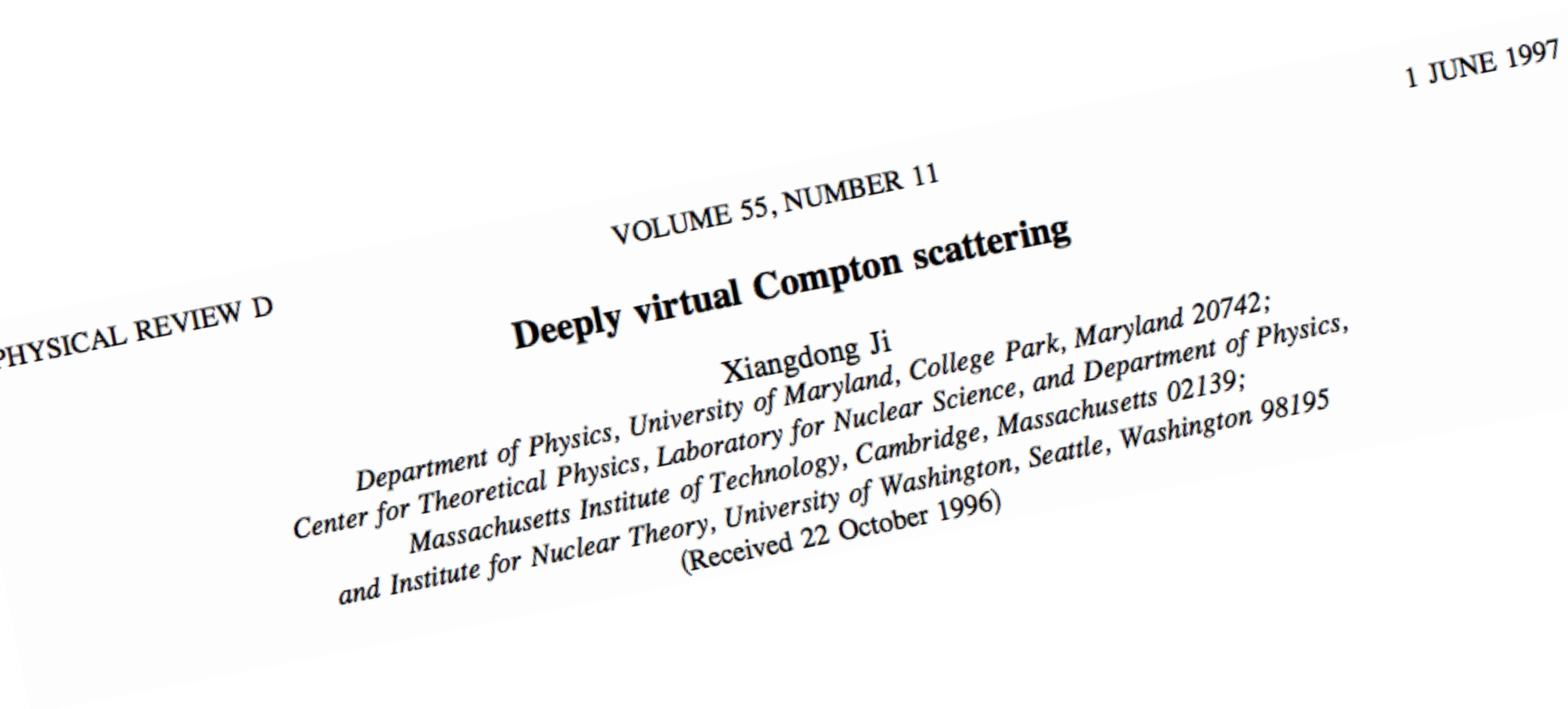
Simonetta Liuti
University of Virginia

Outline

1. Motivation
2. Helicity Amplitudes Formalism for DVCS and TCS
3. Importance of studies twist three contributions to DVCS and TCS: universality
4. Implementation in experimental analyses
5. Conclusions

1. MOTIVATION

DVCS was proposed as an avenue to access GPDs in experiments by Ji in 1997


PHYSICAL REVIEW D VOLUME 55, NUMBER 11 1 JUNE 1997

Deeply virtual Compton scattering

Xiangdong Ji

Department of Physics, University of Maryland, College Park, Maryland 20742;
Center for Theoretical Physics, Laboratory for Nuclear Science, and Department of Physics,
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139;
and Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195

(Received 22 October 1996)

Several papers were written, after that, on the formalism for the deeply virtual exclusive electroproduction cross section

Leading twist asymmetries in deeply virtua
Compton scattering

A.V. Belitsky [a,*], D. Müller [a,b], L. Niedermeier [b], A. S
[a] C.N. Yang Institute for Theoretical Physics, State University of New Yor
NY 11794-3840, Stony Brook, USA
Physik, Universität Regensburg, D-93040
accepted 7 Septemb

PHYSICAL REVIEW D, VOLUME

Deeply virtual electroproduction of photons and
Leading order amplitudes and power

M. Vanderhaeghen
Institut für Kernphysik, Johannes Gutenberg Universität, D-5509
P. A. M. Guichon
CEA-Saclay, DAPNIA/SPhN, F-91191 Gif-sur-Yvette, Fran
M. Guidal
IPN Orsay, F-91406 Orsay, France
ived 17 May 1999; published 8 October 1999)

On the analysis of lepton scattering on longitudinally or transversely polarized protons

M. Diehl[1,a], S. Sapeta[2]

[1] Deutsches Elektronen-Synchroton DESY, 22603 Hamburg, Germany
[2] M. Smoluchowski Institute of Physics, Jagellonian University, Cracow, Poland

Received: 7 March 2005 /
Published online: 24 May 2005 – © Springer-Verlag / Società Italiana di Fisica 2005

The most complete treatment is the work by BKM*

Theory of deeply virtual Compton scattering on the nucleon

A.V. Belitsky [a,b,c], D. Müller [c,d], A. Kirchner [d]

[a] *Department of Physics, University of Maryland at College Park, College Park, MD 20742-4111, USA*
[b] *C.N. Yang Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, NY 11794-3840, USA*
[c] *Fachbereich Physik, Universität Wuppertal, D-42097 Wuppertal, Germany*
[d] *Institut für Theoretische Physik, Universität Regensburg, D-93040 Regensburg, Germany*

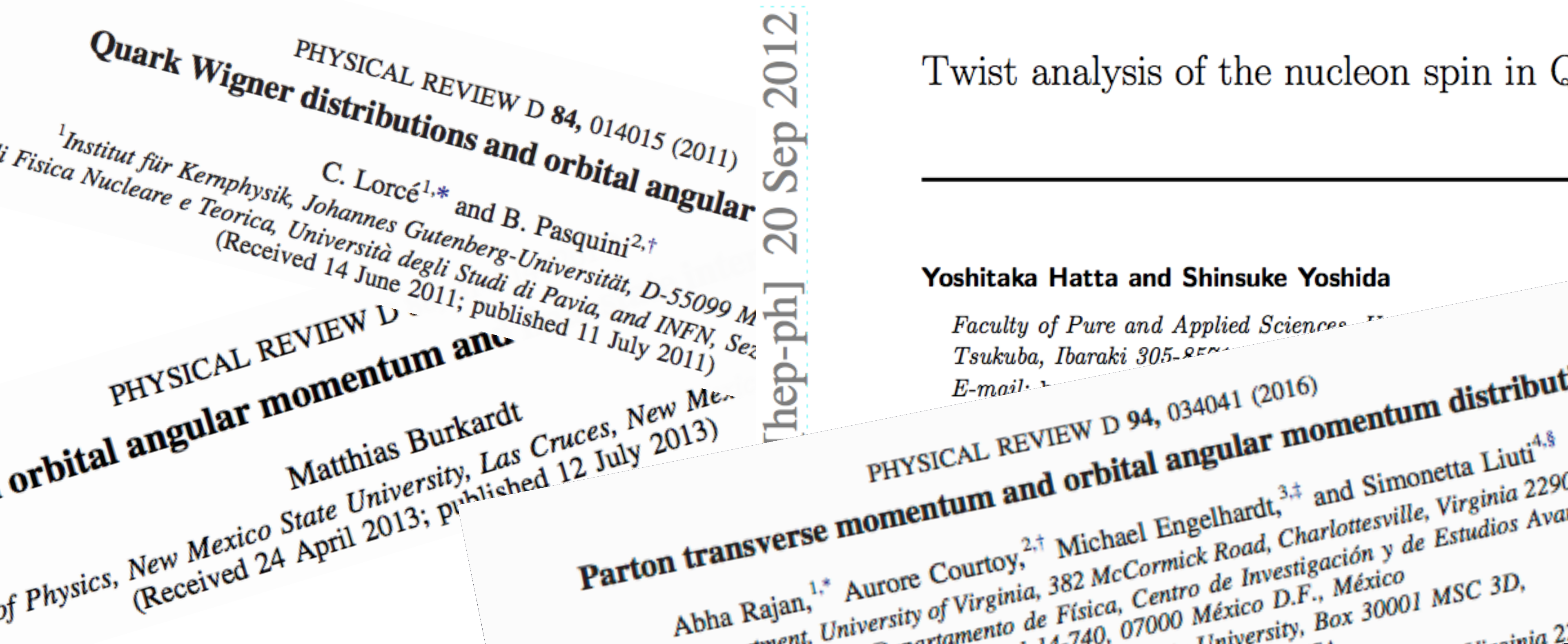
Received 11 December 2001; accepted 25 February 2002

All extractions of leading order GPDs from experiment have been carried out following the BKM formalism

*complemented by several more recent papers

However…

In the past few years new developments have arisen, triggered by the quest for partonic Orbital Angular Momentum, and involving both Generalized Transverse Momentum Distributions (GTMDs) and twist three GPDs

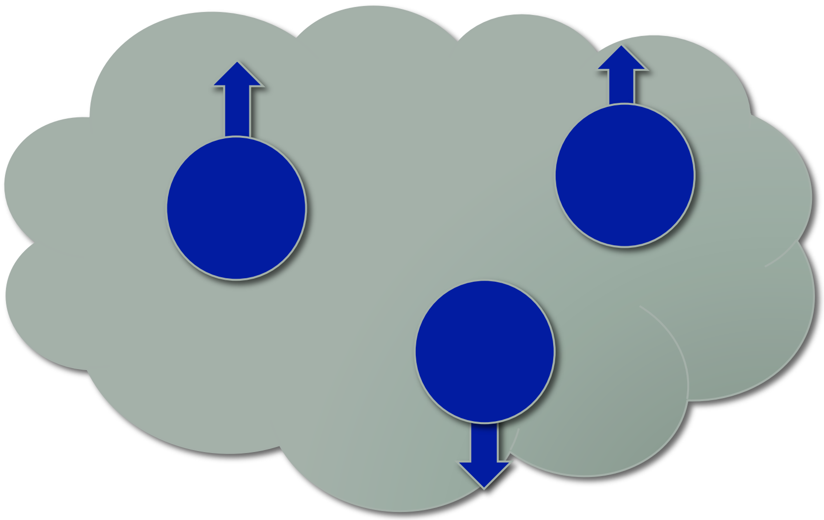


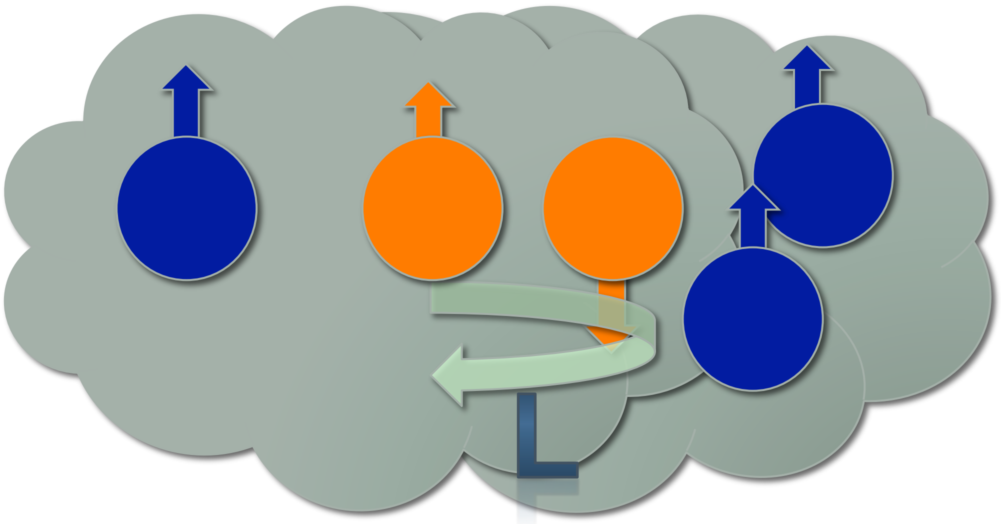
These developments, in turn, point at the importance of understanding QCD at the amplitude level

- Single Spin Asymmetries (SSA) as correlations of **quark/proton spin** and **intrinsic transverse momentum/momentum transfer**

- Through SSA explore how FSI/ISI probe underlying **non-perturbative dynamics**: from **orbital motion and spin correlations** to mechanisms for generating quark-antiquark pairs from flux tube ➔ **dynamical symmetry breaking and confinement properties of the theory**

- This physics involves orbital motion and it is not about "hand waving" models!



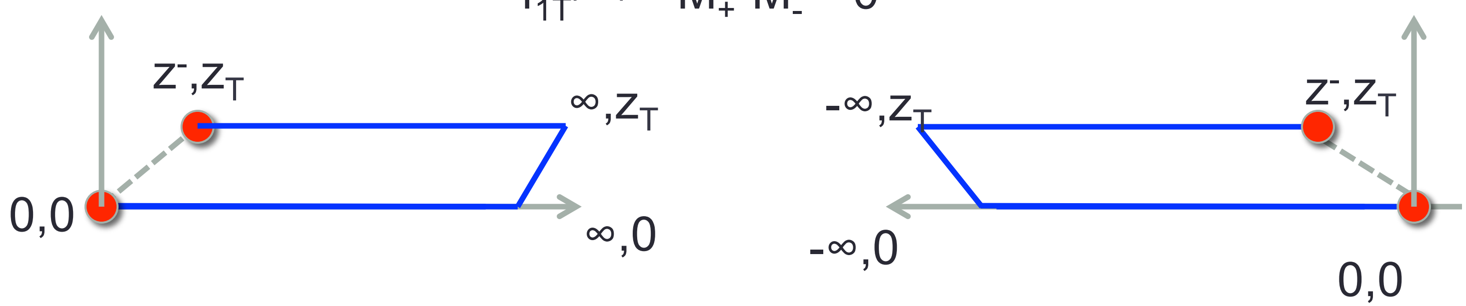


PT transformation

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

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

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



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: GTMD F_{14}

PT:

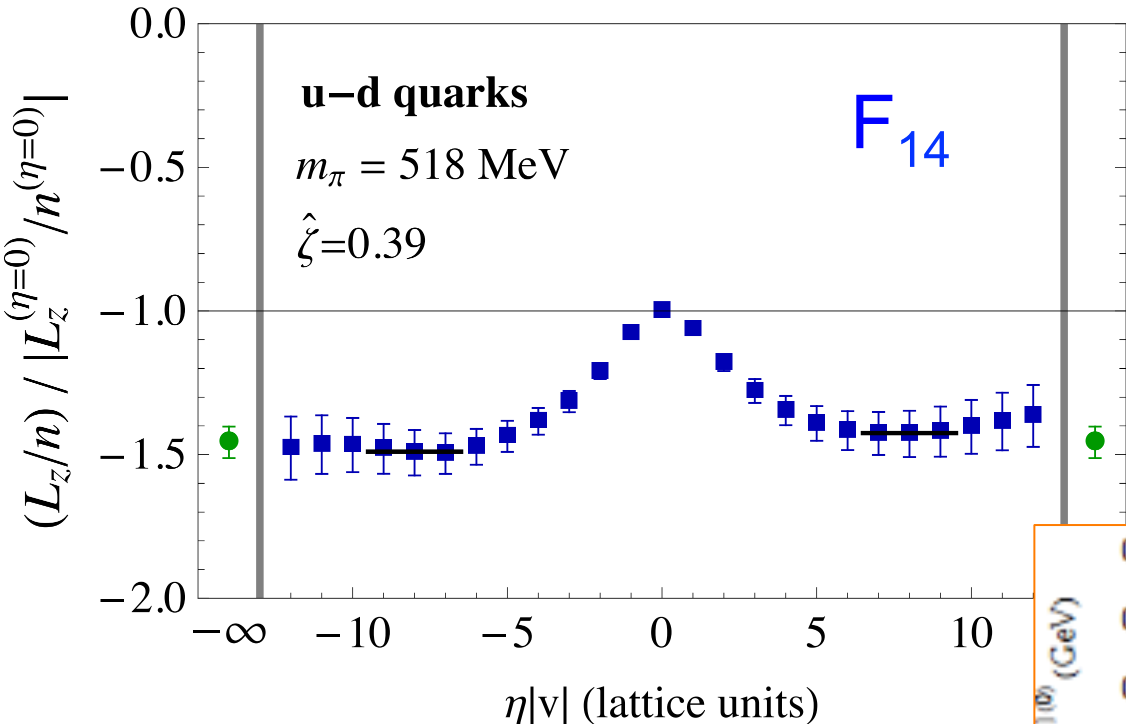
$$\langle P-\Delta, S \mid \bar{\psi}(0)\gamma^{+}U(v,z)\psi(z) \mid P, S\rangle = \langle P, -S \mid \bar{\psi}(0)\gamma^{+}U(-v,z)\psi(z) \mid P-\Delta, -S\rangle$$

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

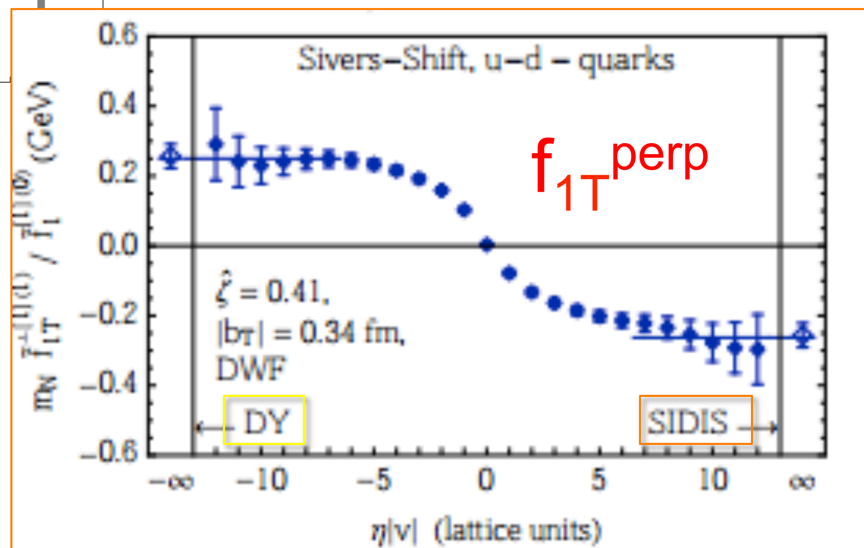
$L_{+}^{v,\Delta}-L_{-}^{-v,-\Delta} = 0$

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

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

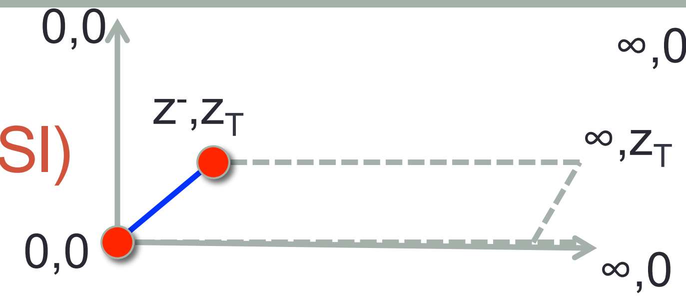


PRD, arXiv:1111.4249



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

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)

OAM is given by a twist 3 GPD

1. L_q^z

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

k_T moment of a GTMD — twist 3 GPD

2. $L_q^z S_q^z$

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

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

The formalism of BKM does not allow us to include this physics in a straightforward way

Additional practical problem: in BKM it is hard to disentangle the Q^2 dependence of the various terms beyond $O(M^2/Q^2, t/Q^2)$ type approximations

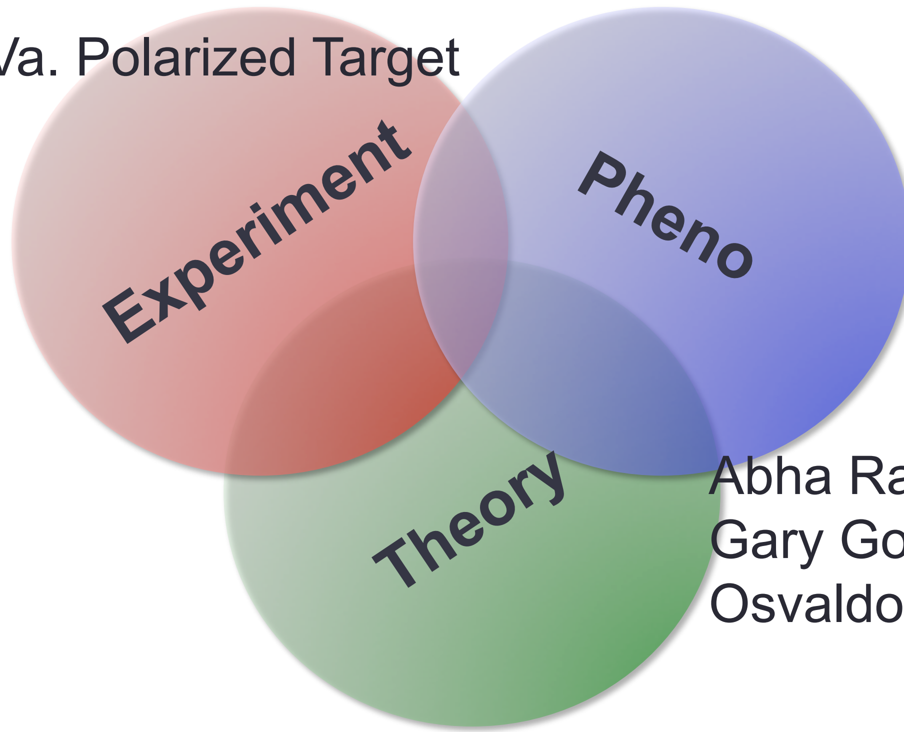
It is timely, in view of the upcoming experiments, to have a formalism that includes in a natural way the recent developments in the cross section of polarized deeply virtual exclusive processes:

- Polarized DVCS
- DVCS with Recoil Polarization
- Timelike Compton Scattering (TCS)
- Double DVCS (DDVCS)
- More exclusive processes leading to the measurement of GTMDs

The formalism we present is based on the helicity amplitudes decomposition of the cross section, and it is more suitable for a direct use in experimental analyses/MCs

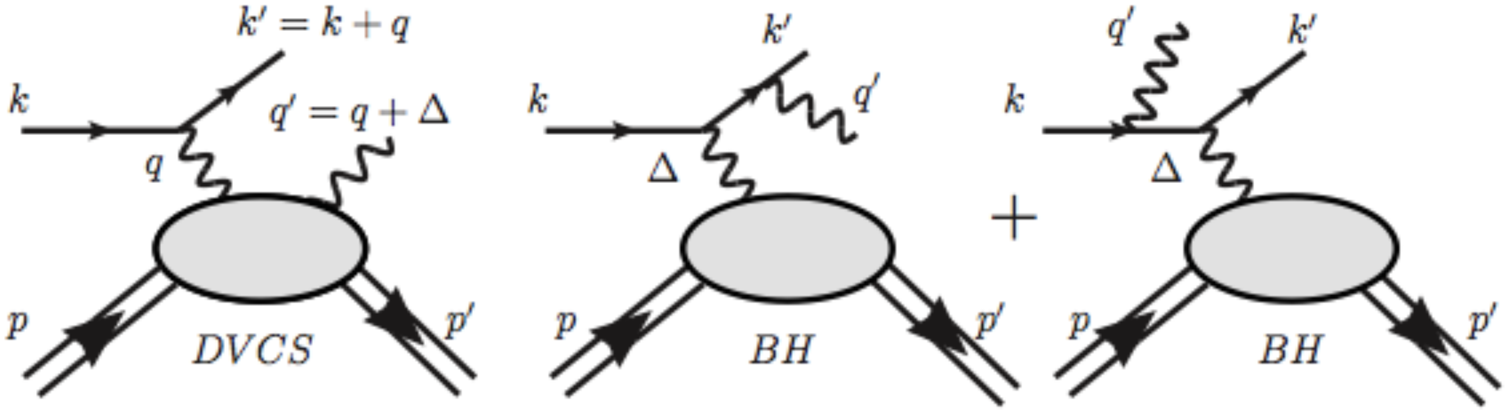
2. HELICITY AMPLITUDES FORMALISM

Dustin Keller & U.Va. Polarized Target Group



Abha Rajan
Gary Goldstein
Osvaldo Gonzalez Hernandez

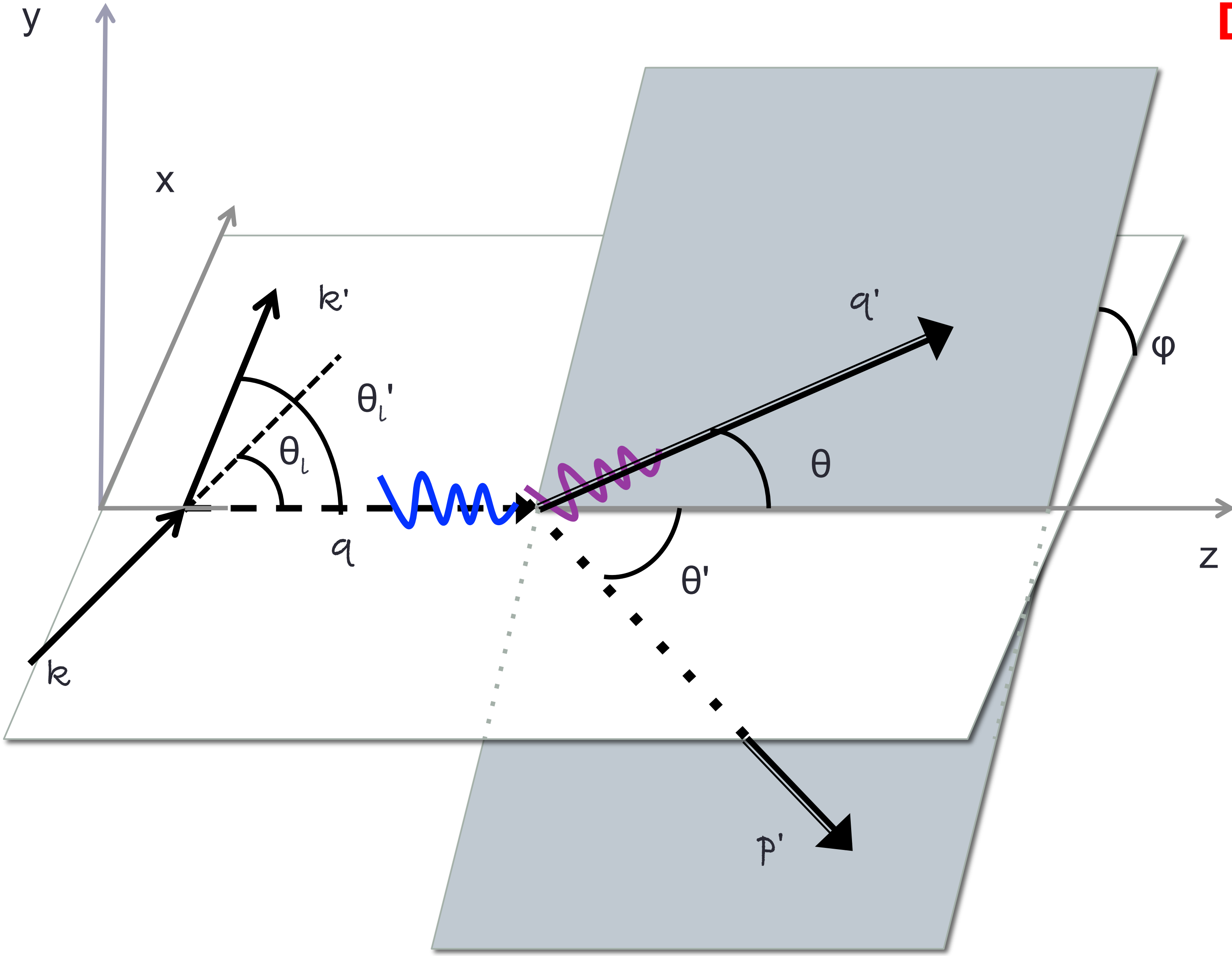
Deeply Virtual Exclusive Photoproduction



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

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

DVCS



We extended to GPDs the formalism used in the forward case (SIDIS)

SIDIS cross section

unpolarized target

$$\frac{d^4\sigma}{dx_{Bj}dyd\phi dt} = \Gamma\Big\{\Big[F_{UU,T} + \epsilon F_{UU,L} + \epsilon\cos 2\phi F_{UU}^{\cos 2\phi} + \sqrt{2\epsilon(\epsilon+1)}\cos\phi F_{UU}^{\cos\phi} + h\sqrt{2\epsilon(1-\epsilon)}\,\sin\phi F_{LU}^{\sin\phi}\Big]$$

longitudinally polarized target

$$+ S_{||}\Big[\sqrt{2\epsilon(\epsilon+1)}\sin\phi F_{UL}^{\sin\phi} + \epsilon\sin 2\phi F_{UL}^{\sin 2\phi} + h\Big(\sqrt{1-\epsilon^2}\,F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\,\cos\phi\,F_{LL}^{\cos\phi}\Big)\Big]$$

transv. polarized

$$+ S_{\perp}\Big[\sin(\phi-\phi_S)\Big(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\Big) + \epsilon\Big(\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)}\Big)$$

$$+ \sqrt{2\epsilon(1+\epsilon)}\Big(\sin\phi_S F_{UT}^{\sin\phi_S} + \sin(2\phi-\phi_S)F_{UT}^{\sin(2\phi-\phi_S)}\Big)\Big]$$

$$+ S_{\perp}h\Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\Big(\cos\phi_S F_{LT}^{\cos\phi_S} + \cos(2\phi-\phi_S)F_{LT}^{\cos(2\phi-\phi_S)}\Big)\Big]\Big\}$$

Angle between hadron and lepton planes

$$F_{UU}^{\cos\varphi}$$

Beam polarization

Target polarization

Forerunners…

Virtual Compton scattering off protons at moderately large momentum transfer

P. Kroll [a,1], M. Schürmann [a,2], P.A.M. Guichon [b,3]

[a] *Fachbereich Physik, Universität Wuppertal, Gaußstrasse 20, D-42097 Wuppertal, Germany*

[b] *SPhN-DAPNIA, CE Saclay, F-91191 Gif sur Yvette, France*

Received 13 July 1995; revised 28 December 1995

Interpretation in terms of structure functions, example

n.p. Q^2 dependence

kinematical factor

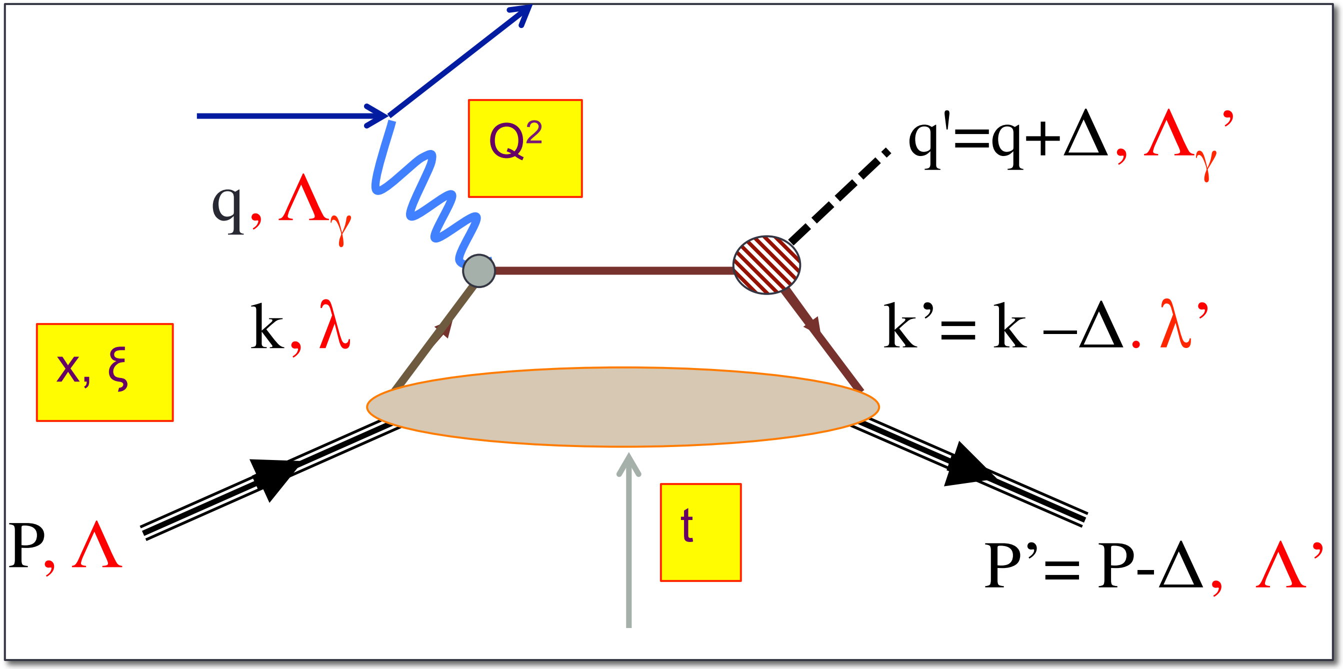
$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xh\,H_1^{\perp} + \frac{M_h}{M}\,f_1\frac{\tilde{D}^{\perp}}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xf^{\perp}D_1 + \frac{M_h}{M}\,h_1^{\perp}\frac{\tilde{H}}{z}\right)\right]$$

structure functions (twist 2 × twist 3)

Convolution over transverse momenta

Extension to DVCS

$$\gamma^* p \to \gamma(M) p'$$



$$\sigma = \sigma^{UU} + h\,\sigma^{LU} + S_{||}\sigma^{UL} + S_{||}h\,\sigma^{LL} + S_T\sigma^{UT} + S_T h\,\sigma^{LT}$$

example

$$\sigma^{UU} = \frac{\Gamma}{2} \sum_{h,\Lambda} \sum_{\Lambda',\Lambda'_\gamma} \left(T^{h\Lambda'_\gamma}_{DVCS,\Lambda\Lambda'}\right)^* T^{h\Lambda'_\gamma}_{DVCS,\Lambda\Lambda'}$$

BASIC MODULE (based on helicity amplitudes)

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

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

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

polarized lepton

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

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

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

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

Phase dependence

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

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

Interpretation in terms of GPDs

Twist 2

$$A_{++,++} = \sqrt{1-\xi^2}\left(\frac{H+\widetilde{H}}{2} - \frac{\xi^2}{1-\xi}\frac{E+\widetilde{E}}{2}\right)$$

$$A_{+-,+-} = \sqrt{1-\xi^2}\left(\frac{H-\widetilde{H}}{2} - \frac{\xi^2}{1-\xi}\frac{E-\widetilde{E}}{2}\right)$$

$$A_{++,-+} = -\frac{\Delta_1 + i\Delta_2}{t_0 - t}\frac{t_0 - t}{2M}\frac{E - \xi\widetilde{E}}{2}$$

$$A_{-+,++} = \frac{\Delta_1 - i\Delta_2}{t_0 - t}\frac{t_0 - t}{2M}\frac{E + \xi\widetilde{E}}{2}$$

$$f^{11}_{++} = \sqrt{1-\xi^2}\left(\mathcal{H} + \widetilde{\mathcal{H}} - \frac{\xi^2}{1-\xi^2}(\mathcal{E} + \widetilde{\mathcal{E}})\right)$$

$$f^{11}_{--} = \sqrt{1-\xi^2}\left(\mathcal{H} - \widetilde{\mathcal{H}} - \frac{\xi^2}{1-\xi^2}(\mathcal{E} - \widetilde{\mathcal{E}})\right)$$

$$f^{11}_{+-} = e^{-i\phi}\frac{\sqrt{t_0 - t}}{2M}(\mathcal{E} + \xi\widetilde{\mathcal{E}})$$

$$f^{11}_{-+} = -e^{i\phi}\frac{\sqrt{t_0 - t}}{2M}(\mathcal{E} - \xi\widetilde{\mathcal{E}})$$

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

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

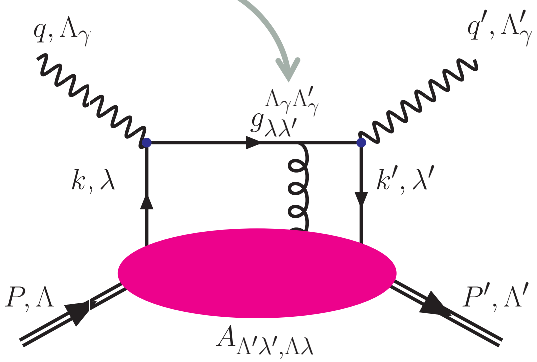
$$F^{11}_{+-} = \frac{t_0 - t}{4M^2} \mid \mathcal{E} + \xi \widetilde{\mathcal{E}} \mid^2$$

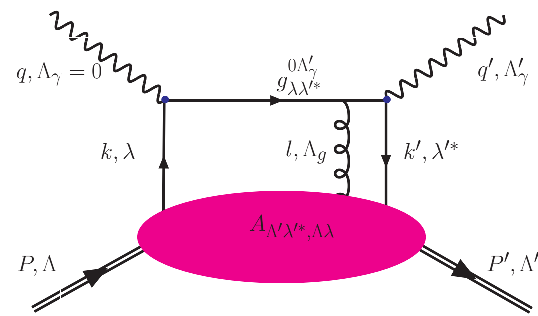
$$F^{11}_{-+} = \frac{t_0 - t}{4M^2} \mid \mathcal{E} - \xi \widetilde{\mathcal{E}} \mid^2$$

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 chirality)





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

Example

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

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

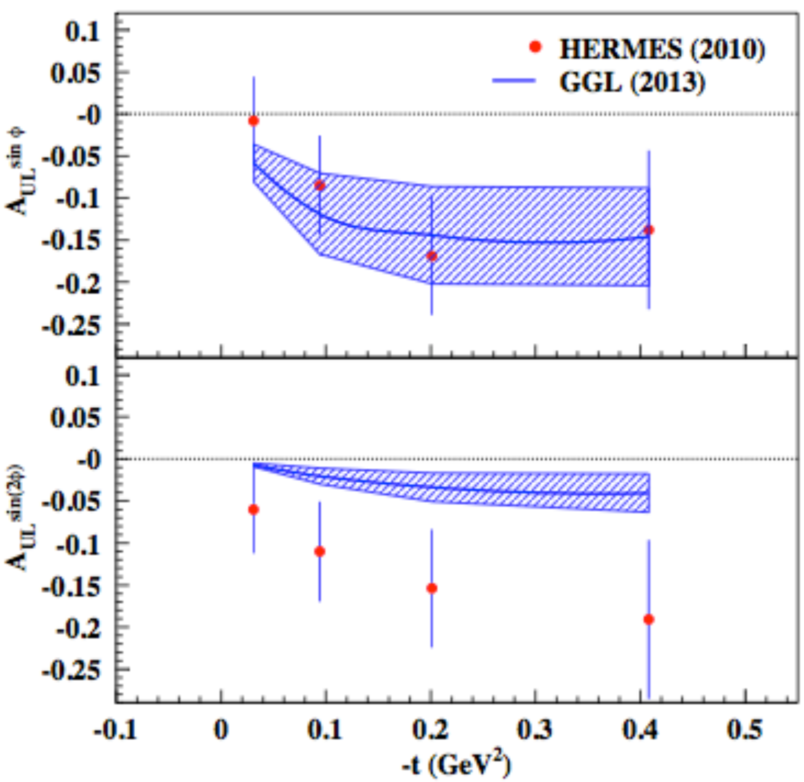
$$\vdots$$

Orbital angular momentum

Spin Orbit interaction

DVCS: bilinears of tw 2 and tw 3 CFFs

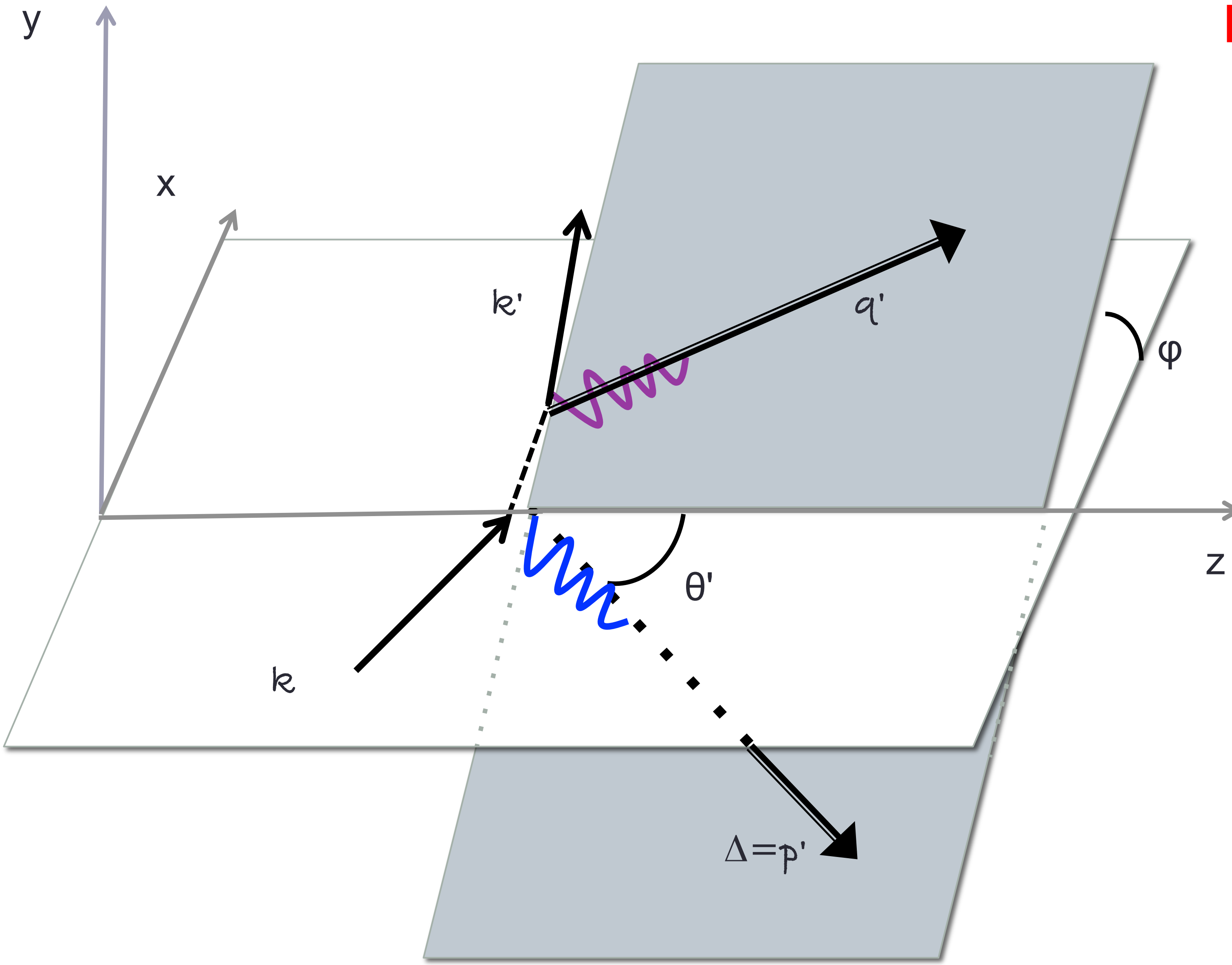
$$F^{01}_{++} = \mathcal{P}\left[\mathcal{H}^*(\tilde{\mathcal{E}}_{2T} - \bar{\mathcal{E}}_{2T} + \ldots), \ldots\right]$$



Preliminary extraction from experiment using Wandzura Wilczek approximation

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

BH



BH Amplitude

$$T^{h\Lambda'_\gamma}_{BH,\Lambda,\Lambda'}(k,p,k',q',p') = \frac{1}{\Delta^2}\sum_{\tilde{\Lambda}_\gamma} B^{\tilde{\Lambda}_\gamma}_{h,\Lambda'_\gamma}(k,k',q')J^{\tilde{\Lambda}_\gamma}_{\Lambda\Lambda'}(p,p'),$$

Lepton part

$$\bar{u}(k',h)\left[\gamma^\mu(\not{k}'+\not{q}')\gamma^\nu\frac{1}{(k'+q')^2}+\gamma^\nu(\not{k}-\not{q}')\gamma^\mu\frac{1}{(k-q')^2}\right]u(k,h)\epsilon^{*\Lambda'_\gamma}_\mu(q')\epsilon^{*\tilde{\Lambda}_\gamma}_\nu(\Delta)/\Delta^2$$

$$= L^{\mu\nu}_h\epsilon^{*\Lambda'_\gamma}_\mu(q')\epsilon^{*\tilde{\Lambda}_\gamma}_\nu(\Delta) = B^{\tilde{\Lambda}_\gamma}_{h,\Lambda'_\gamma}. \quad (10$$

Hadron part

$$\overline{U}(p',\Lambda')\Gamma_\nu U(p,\Lambda) = \overline{U}(p',\Lambda')\left[\left(F_1(-\Delta^2)+F_2(-\Delta^2)\right)\gamma^\nu - \frac{(p+p')^\nu}{2M}F_2(-\Delta^2)\right]U(p,\Lambda),$$

The BH term can be calculated exactly (QED+ proton form factors)

Gonzalez, Rajan

$$\begin{aligned}
\tilde{B}^{\tilde{\Lambda}_\gamma\,(1)}_{h,\Lambda'_\gamma} = &\left\{\sqrt{\frac{\gamma^2 y^2+4y-4}{y-1}}\left(\frac{x_B M_p}{4\gamma^2}\right)\left(2h\left(\tilde{\Lambda}_\gamma\cos(\theta')-\cos(\theta)\Lambda'_\gamma\right)\frac{\gamma^2}{\sqrt{\gamma^2+1}}+\right.\right.\\
&\left.\left.\left(\tilde{\Lambda}_\gamma\Lambda'_\gamma\left(\gamma^2\cos(\theta)\cos(\theta')-2\sin(\theta)\sin(\theta')\right)-\gamma^2\right)\frac{(y-2)}{(\gamma^2+1)\,y}\right)\right\}\\
&+\cos(\phi)\left\{\left(\frac{x_B M_p}{2\gamma}\right)\Lambda'_\gamma\left[\tilde{\Lambda}_\gamma\left(\sin(\theta-\theta')\frac{4\sqrt{1-y}}{(\gamma^2+1)\,y}+\sin(\theta+\theta')\frac{y}{(\gamma^2+1)\sqrt{1-y}}-\right.\right.\right.\\
&\left.\left.\left.\cos(\theta)\sin(\theta')\frac{(1-\gamma^2)y}{(\gamma^2+1)\sqrt{1-y}}\right)+2h\sin(\theta)\frac{(2-y)}{\sqrt{\gamma^2+1}\sqrt{1-y}}\right]\right\}\\
&-\cos(2\phi)\left\{\sqrt{\frac{\gamma^2 y^2+4y-4}{y-1}}\left(\frac{x_B M_p}{4}\right)\left(\left(1+\tilde{\Lambda}_\gamma\cos(\theta)\Lambda'_\gamma\cos(\theta')\right)\frac{(2-y)}{(\gamma^2+1)\,y}+\right.\right.\\
&\left.\left.2h\left(\tilde{\Lambda}_\gamma\cos(\theta')+\cos(\theta)\Lambda'_\gamma\right)\frac{1}{\sqrt{\gamma^2+1}}\right)\right\}\\
&+\sin(\phi)\left\{i\left(\frac{x_B M_p}{2\gamma}\right)\left(\tilde{\Lambda}_\gamma\sin(\theta')\frac{(\gamma^2y^2+4y-4)}{(\gamma^2+1)\sqrt{1-y}\,y}-\right.\right.\\
&\left.\left.2h\tilde{\Lambda}_\gamma\Lambda'_\gamma\sin(\theta)\cos(\theta')\frac{(y-2)}{\sqrt{\gamma^2+1}\sqrt{1-y}}+\Lambda'_\gamma\sin(\theta)\frac{(y-2)^2}{(\gamma^2+1)\sqrt{1-y}\,y}\right)\right\}\\
&-\sin(2\phi)\left\{\sqrt{\frac{\gamma^2 y^2+4y-4}{y-1}}\left(\frac{x_B M_p}{4}\right)\left(i2h\left(1+\tilde{\Lambda}_\gamma\cos(\theta)\Lambda'_\gamma\cos(\theta')\right)\frac{1}{\sqrt{\gamma^2+1}}+\right.\right.\\
&\left.\left.\left(\tilde{\Lambda}_\gamma\cos(\theta')+\cos(\theta)\Lambda'_\gamma\right)\frac{(2-y)}{(\gamma^2+1)\,y}\right)\right\} \qquad (3)
\end{aligned}$$

- 1 of 5 numerator terms for the lepton part!
- Additional φ dependence in denominators
- Additional φ dependence from hadron current

BH-DVCS interference

$$\mathcal{I} = \left(T^{h\Lambda'_\gamma\,*}_{BH,\,\Lambda\Lambda'} T^{h\Lambda'_\gamma}_{DVCS,\,\Lambda\Lambda'} + T^{h\Lambda'_\gamma\,*}_{DVCS,\,\Lambda\Lambda'} T^{h\Lambda'_\gamma}_{BH,\,\Lambda\Lambda'} \right)$$

BASIC MODULE

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

$$= \sum_{\Lambda'_\gamma, \Lambda'} \left(T^{h\Lambda'_\gamma}_{BH,\Lambda\Lambda'}\right)^* \sum_{\Lambda_{\gamma^*}} A_h^{\Lambda_{\gamma^*}} f^{\Lambda_{\gamma^*},\Lambda'_\gamma}_{\Lambda,\Lambda'} + \left(T^{h\Lambda'_\gamma}_{BH,\Lambda\Lambda'}\right) \sum_{\Lambda_{\gamma^*}} A_h^{\Lambda_{\gamma^*}} (f^{\Lambda_{\gamma^*},\Lambda'_\gamma}_{\Lambda,\Lambda'})^*$$

$$= 2 \sum_{\Lambda_{\gamma^*}} A_h^{\Lambda_{\gamma^*}} \mathrm{Re}\, T^{h\Lambda'_\gamma}_{BH,\Lambda\Lambda'} \mathrm{Re} f^{\Lambda_{\gamma^*},\Lambda'_\gamma}_{\Lambda,\Lambda'} + 2 \sum_{\Lambda_{\gamma^*}} A_h^{\Lambda_{\gamma^*}} \mathrm{Im}\, T^{h\Lambda'_\gamma}_{BH,\Lambda\Lambda'} \mathrm{Im} f^{\Lambda_{\gamma^*},\Lambda'_\gamma}_{\Lambda,\Lambda'}$$

- Phase dependence allowing us to separate out tw 2 from tw 3 terms comes entirely from here

- The rest is a “contamination” that we calculate exactly

3. IMPORTANCE OF DVCS AND TCS COMPARISON

All the formalism shown above is extended straightforwardly to TCS

In TCS there are important differences:

- one can use the linearly polarized photons to measure the asymmetries sensitive to the polarized GPDs (Goritschnig, Pire, Wagner, PRD 2014) …

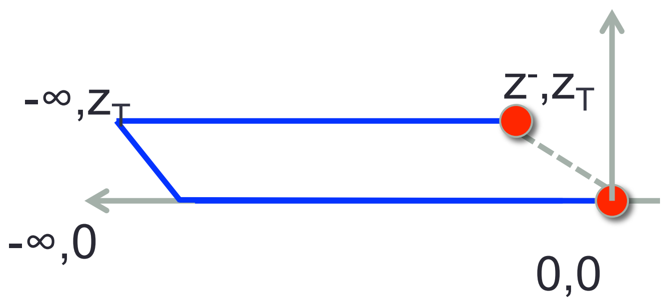
- NLO weighs more

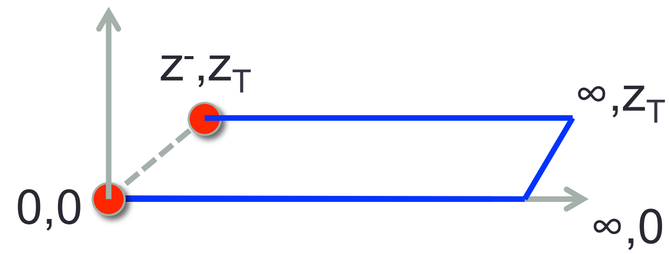
- etc.…

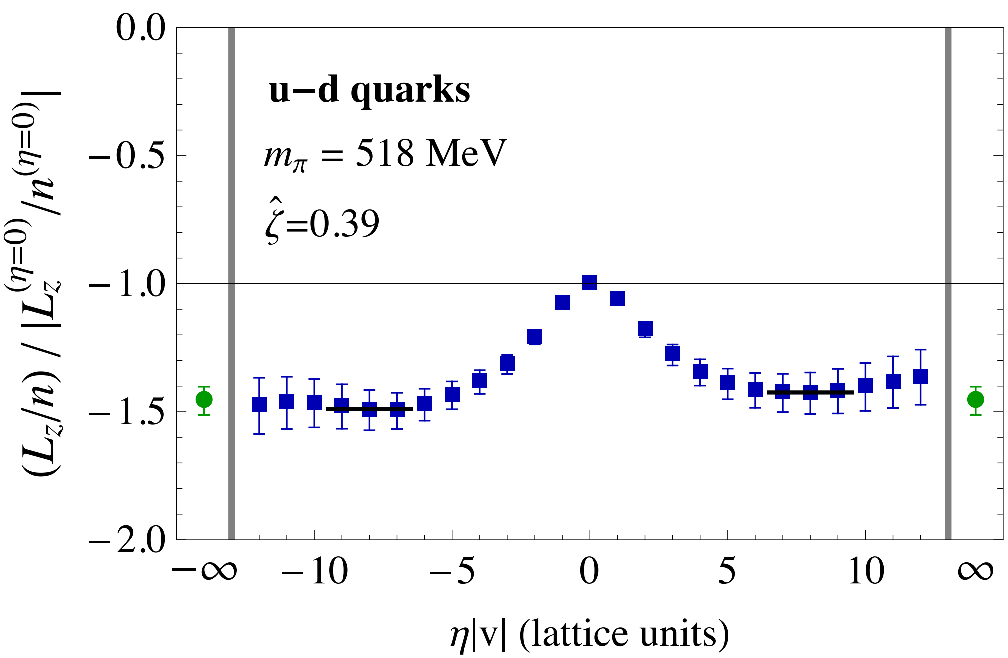
… but we don’t want to use TCS as an ancillary process to DVCS!

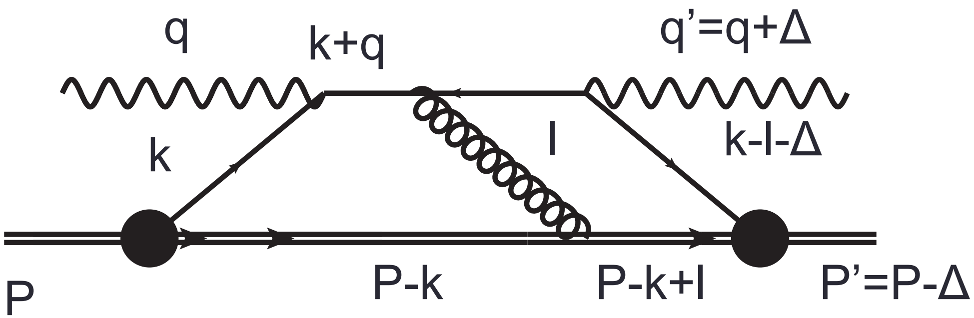
An argument that cannot be refused…

Universality/process dependence of parton distributions



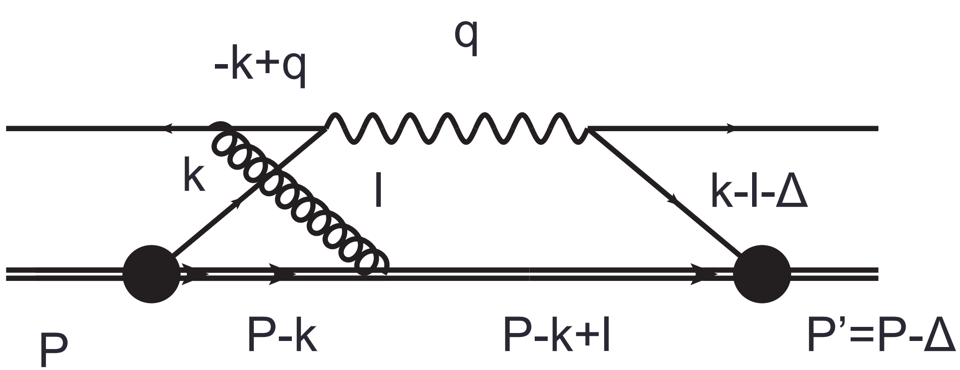






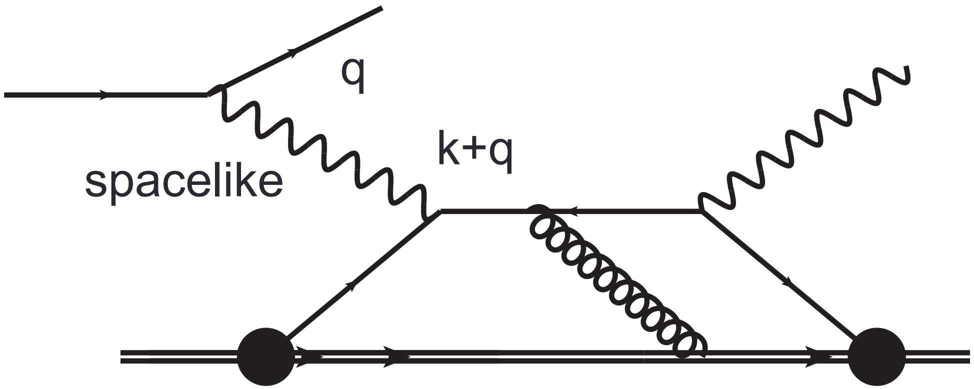
"SIDIS-like"

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

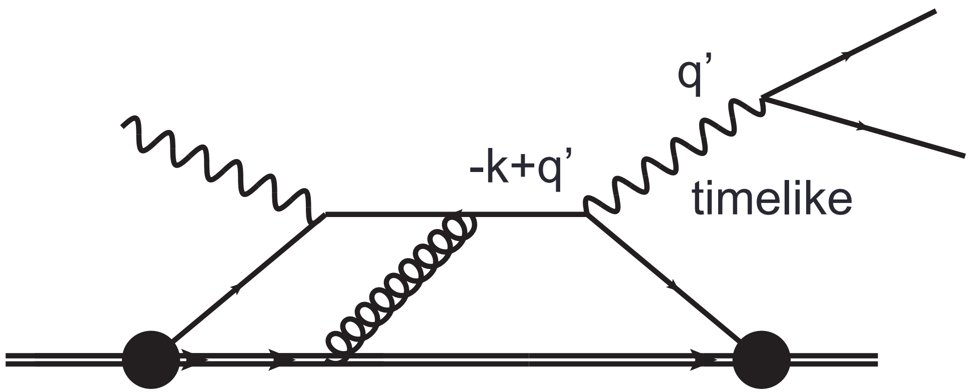


"DrellYan-like"

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"

4. IMPLEMENTATION IN EXPERIMENTAL ANALYSES

Implementation in experimental analysis

- We provide (Dustin) with all the necessary terms that are necessary to extract any given observable (for example we focused on the unpolarized cross section)
- We run the MC with model GPDs to validate the procedure by verifying that the initial model corresponds to the output
- We have a tool that can be both tested with other models and used with real data to constrain the models parameters and to obtain GPD shapes

A variety of GPD models

- Extracting GPD from increasingly precise sets of data will involve elements of Information Theory
(see D. Ireland, analysis of pseudoscalar meson photoproduction PRD82 2010)

- Issue of finding a parametric functional form given the enhanced complexity (neural network? E. Askanazi and S.L., JPhys G42, 2015)

- From the structure functions of DIS

$$f(x,Q_o^2) = A_{q,g}\, x^{-\alpha_{q,g}} (1-x)^{\beta_{q,g}} F(x, c_{q,g}, d_{q,g}, \ldots)$$

↓

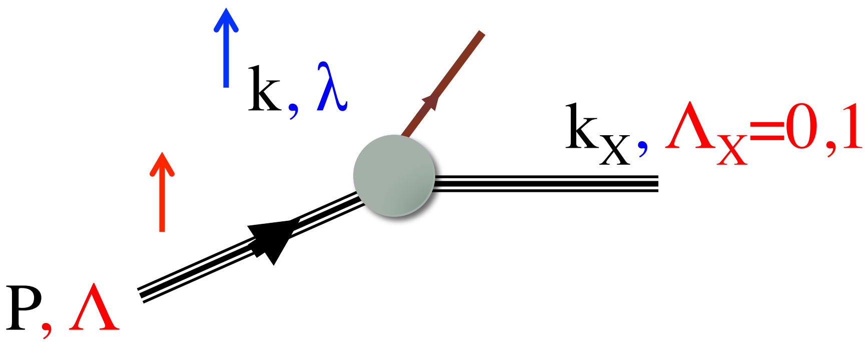
to the Compton Form Factors of DVCS, DVMP, TCS, …

$$H_{q_v}(x,\xi,t;Q_o^2) =$$

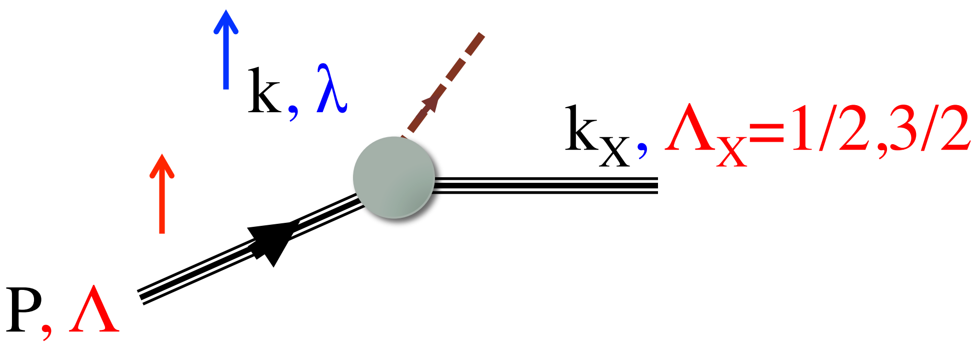
$$H_{\bar{q}}(x,\xi,t;Q_o^2) = \qquad ?$$

$$H_g(x,\xi,t;Q_o^2) =$$

Covariant Scattering Matrix/spectator model



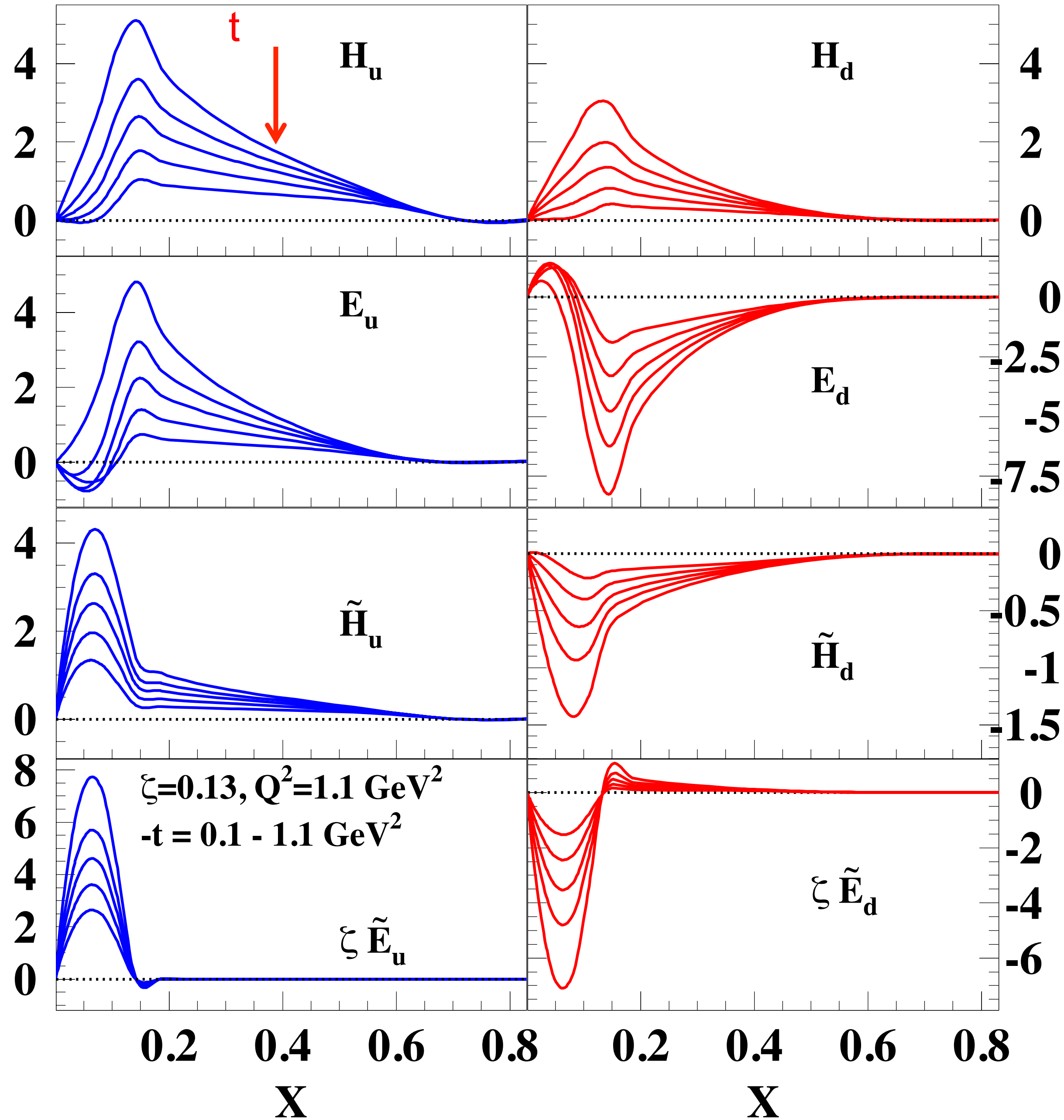
k = **quark, anti-quark** (flavor separation from combination of Λ_X=0,1)



k = **gluon**

Quark GPDs (with Hessian error not shown)

x_{Bj}=0.13
Q^2=1.1 GeV^2
0.1 < -t < 1.1 GeV^2

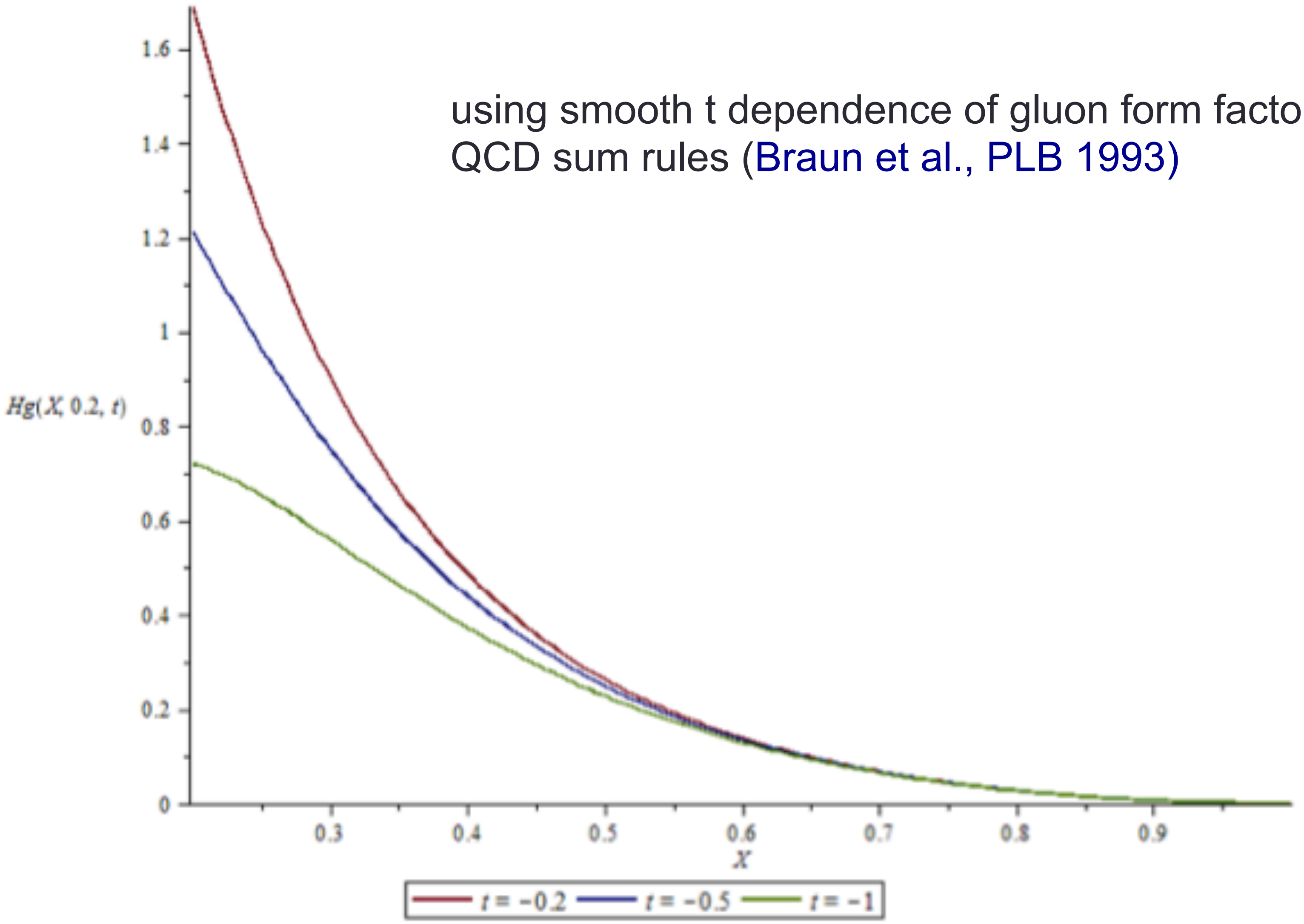


Valence quarks parameters constrained by polynomiality

Parameters	H	E	$\widetilde{H}$	$\widetilde{E}$
m_u (GeV)	0.420	0.420	2.624	2.624
M_X^u (GeV)	0.604	0.604	0.474	0.474
M_Λ^u (GeV)	1.018	1.018	0.971	0.971
α_u	0.210	0.210	0.219	0.219
α'_u	2.448 ± 0.0885	2.811 ± 0.765	1.543 ± 0.296	5.130 ± 0.101
p_u	0.620 ± 0.0725	0.863 ± 0.482	0.346 ± 0.248	3.507 ± 0.054
$\mathcal{N}_u$	2.043	1.803	0.0504	1.074
χ^2	0.773	0.664	0.116	1.98
m_d (GeV)	0.275	0.275	2.603	2.603
M_X^d (GeV)	0.913	0.913	0.704	0.704
M_Λ^d (GeV)	0.860	0.860	0.878	0.878
α_d	0.0317	0.0317	0.0348	0.0348
α'_d	2.209 ± 0.156	1.362 ± 0.585	1.298 ± 0.245	3.385 ± 0.145
p_d	0.658 ± 0.257	1.115 ± 1.150	0.974 ± 0.358	2.326 ± 0.137
$\mathcal{N}_d$	1.570	-2.800	-0.0262	-0.966
χ^2	0.822	0.688	0.110	1.00

Gluons in DGLAP region

using smooth t dependence of gluon form factor from QCD sum rules (Braun et al., PLB 1993)

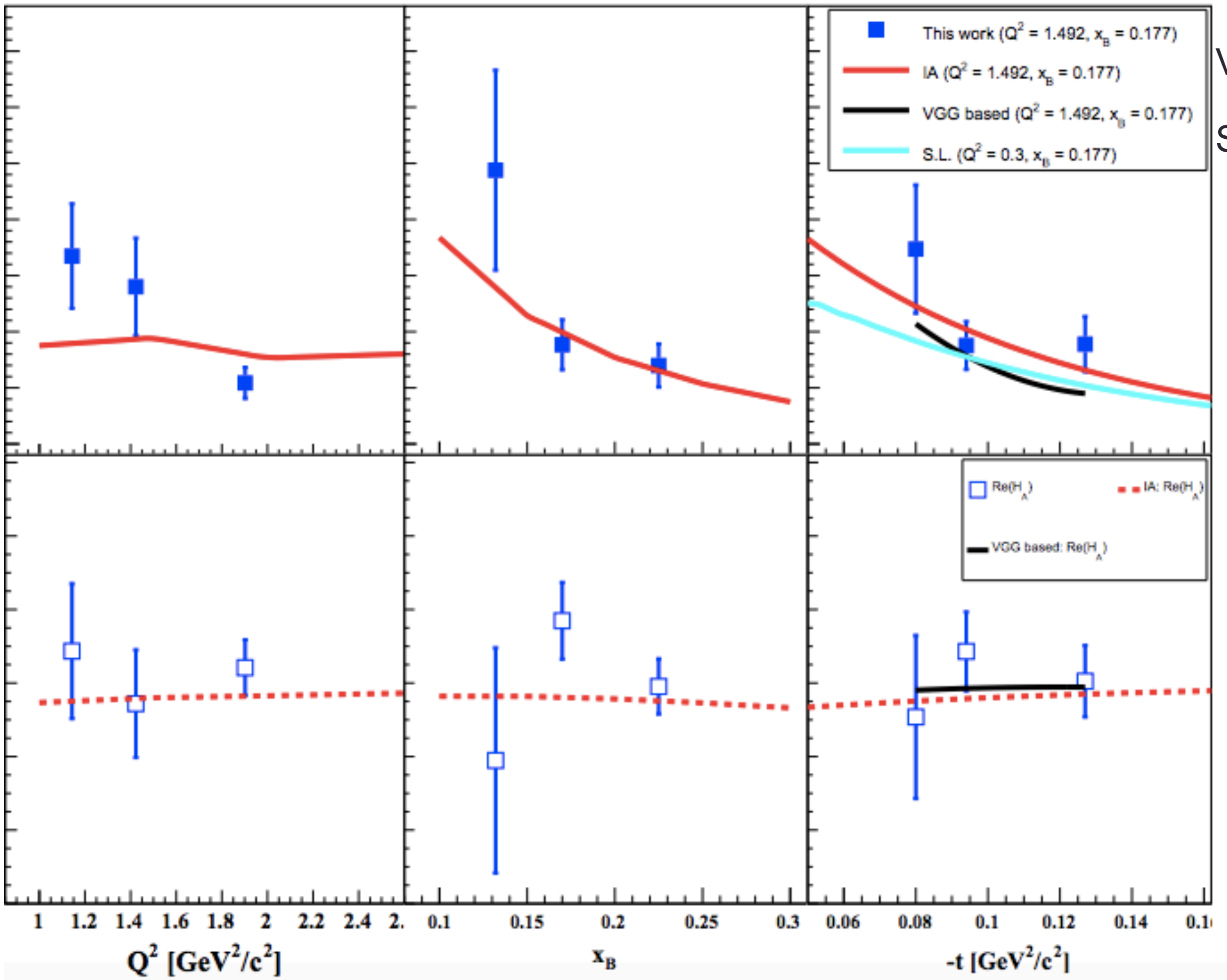


Nuclei: DVCS from ^{4}He EG6, M. Hattawy et al.

tw 2

Im H_A

Re H_A



V. Guzey

S.L.

One can measure the spin orbit term as a **twist 3** spin orbit correlation in ^{4}He!

Conclusions

- A wealth of physics studies on QCD at the amplitude level can be extracted from the comparison of DVCS and TCS
- We presented an helicity based formalism for deeply virtual exclusive electron proton scattering processes
- This formalism allows us to interpret the DVCS cross section twist three GPDs contribution in a clear way, because it organizes the spurious Q^2 dependence from both the BH contamination and from kinematical terms
- It also allows us to connect to experiment directly (analyses using data are on their way)
- Complete results for TCS are on their way

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