Extraction of nucleon 3D structure from DVCS data

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The Nature of Hadron Mass and Quark-Gluon Confinement
from JLab Experiments in the 12-GeV Era
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EUROPSKI STRUKTURNI
I INVESTICIJSKI FONDOVI

Outline

1. Introduction to Generalized Parton Distributions (GPDs) and Deeply Virtual Compton Scattering (DVCS)
2. Global model fits
3. D-term
4. Higher twists
5. Outlook

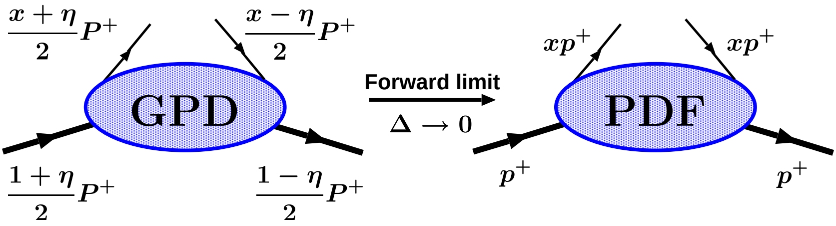
Definition of GPDs

- In QCD GPDs are defined as [Müller '92, et al. '94, Ji, Radyushkin '96]

$$F^q(x,\eta,t) = \int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \langle P_2|\bar{q}(-z)\gamma^+ q(z)|P_1\rangle\Big|_{z^+=0,\,\mathbf{z}_\perp=\mathbf{0}}$$

$$\widetilde{F}^q(x,\eta,t) = \int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \langle P_2|\bar{q}(-z)\gamma^+\gamma_5 q(z)|P_1\rangle\Big|_{z^+=0,\,\mathbf{z}_\perp=\mathbf{0}}$$

(and similarly for gluons F^g and $\widetilde{F}^g$).



$P = P_1 + P_2\;;\qquad t = \Delta^2 = (P_2 - P_1)^2\;;\qquad \eta = -\frac{\Delta^+}{P^+}$ (skewedness)

Some properties of GPDs

- Decomposing into spin-non-flip and spin-flip part:

$$F^a = \frac{\bar{u}(P_2)\gamma^+ u(P_1)}{P^+} H^a + \frac{\bar{u}(P_2) i\sigma^{+\nu} u(P_1)\Delta_\nu}{2MP^+} E^a \qquad a = q, g$$

$$\tilde{F}^a = \frac{\bar{u}(P_2)\gamma^+ \gamma_5 u(P_1)}{P^+} \tilde{H}^a + \frac{\bar{u}(P_2)\gamma_5 u(P_1)\Delta^+}{2MP^+} \tilde{E}^a \qquad a = q, g$$

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- Ji's "sum rule" (related to proton spin problem)

$$J^q = \frac{1}{2} \int_{-1}^{1} dx\, x \Big[H^q(x, \eta, t) + E^q(x, \eta, t) \Big]_{t \to 0} \qquad \text{[Ji '96]}$$

(where E is poorly constrained by present data)

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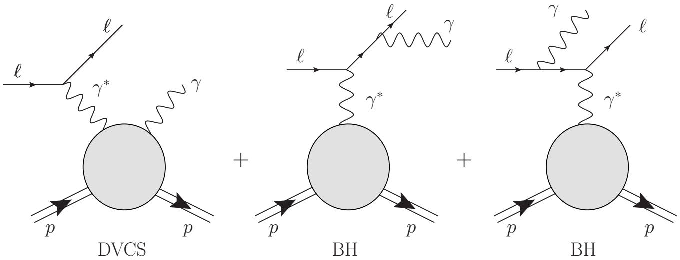
- Distribution of partons in transversal space

$$\rho(x, \vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} e^{-i\vec{b}_\perp \cdot \vec{\Delta}_\perp} H(x, 0, -\vec{\Delta}_\perp^2) \qquad \text{[Burkardt '00]}$$

(where experiments are mostly sensitive to $H(x,x,t)$)

Access to GPDs via DVCS

- Deeply virtual Compton scattering (DVCS) — "gold plated" process of exclusive physics
- DVCS is measured via leptoproduction of a photon



- Interference with Bethe-Heitler process gives unique access to both real and imaginary part of DVCS amplitude.

DVCS cross section

$$d\sigma \propto |\mathcal{T}|^2 = |\mathcal{T}_{\rm BH}|^2 + |\mathcal{T}_{\rm DVCS}|^2 + \mathcal{I} \,.$$

$$\mathcal{I} \quad \propto \quad \frac{-e_\ell}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left\{ c_0^{\mathcal{I}} + \sum_{n=1}^{3}\left[c_n^{\mathcal{I}}\cos(n\phi) + s_n^{\mathcal{I}}\sin(n\phi)\right]\right\},$$

$$|\mathcal{T}_{\rm DVCS}|^2 \quad \propto \quad \left\{ c_0^{\rm DVCS} + \sum_{n=1}^{2}\left[c_n^{\rm DVCS}\cos(n\phi) + s_n^{\rm DVCS}\sin(n\phi)\right]\right\},$$

- Choosing polarizations (and charges) we focus on particular harmonics:

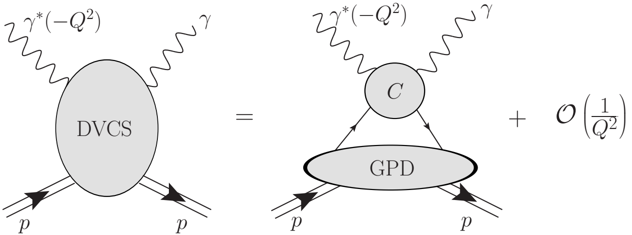
$$c^{\mathcal{I}}_{1,{\rm unpol.}} \propto \left[F_1\,\mathfrak{Re}\,\mathcal{H} - \frac{t}{4M_p^2}F_2\,\mathfrak{Re}\,\mathcal{E} + \frac{x_{\rm B}}{2-x_{\rm B}}(F_1+F_2)\,\mathfrak{Re}\,\widetilde{\mathcal{H}}\right]$$

[Belitsky, Müller et. al '01–'14]

- $\mathcal{H}(x_{\rm B}, t, \mathcal{Q}^2), \ldots$ — four Compton form factors (CFFs)

Factorization of DVCS $\longrightarrow$ GPDs

- [Collins et al. '98]



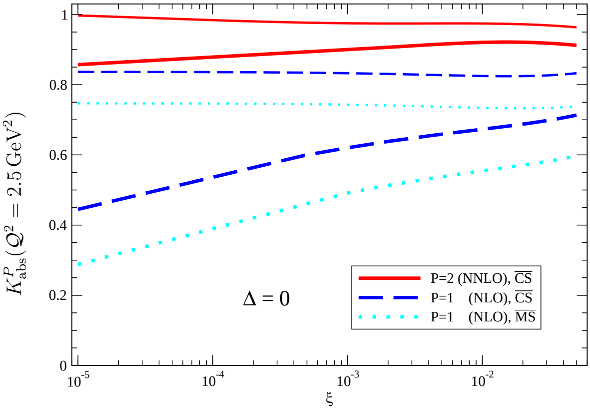
- Compton form factor is a convolution:

$$^{a}\mathcal{H}(x_{\rm B}, t, \mathcal{Q}^2) = \int \mathrm{d}x \; C^a\Big(x, \frac{x_{\rm B}}{2-x_{\rm B}}, \frac{\mathcal{Q}^2}{\mathcal{Q}_0^2}\Big) \, H^a\Big(x, \frac{x_{\rm B}}{2-x_{\rm B}}, t, \mathcal{Q}_0^2\Big)_{a=q,G}$$

- $H^a(x, \eta, t, \mathcal{Q}_0^2)$ — Generalized parton distribution (GPD)

(N)NLO corrections

- [K.K., Müller and Passek-K. '07]



Thick lines:
"hard" gluon
$N_G = 0.4$
$\alpha_G(0) = \alpha_\Sigma(0) + 0.05$

Thin lines:
"soft" gluon
$N_G = 0.3$
$\alpha_G(0) = \alpha_\Sigma(0) - 0.02$

$$K^P_{\rm abs} \equiv \left| \frac{\mathcal{H}^{(P)}}{\mathcal{H}^{(P-1)}} \right|$$

Status of fits

Hybrid GPD models for global fits

- Sea quarks and gluons modelled using SO(3) partial wave expansion in conformal GPD moment space + $\mathcal{Q}^2$ evolution.
- Valence quarks — model CFFs directly (ignoring $\mathcal{Q}^2$ evolution):

$$\mathfrak{Im}\,\mathcal{H}(\xi,t) = \pi\left[\frac{4}{9}H^{u_{\rm val}}(\xi,\xi,t) + \frac{1}{9}H^{d_{\rm val}}(\xi,\xi,t) + \frac{2}{9}H^{\rm sea}(\xi,\xi,t)\right]$$

$$H(x,x,t) = n\,r\,2^{\alpha}\left(\frac{2x}{1+x}\right)^{-\alpha(t)}\left(\frac{1-x}{1+x}\right)^{b}\frac{1}{\left(1-\frac{1-x}{1+x}\frac{t}{M^2}\right)^{p}}\,.$$

- $\mathfrak{Re}\,\mathcal{H}$ determined by dispersion relations
- 15 free parameters in total for H, $\tilde{H}$, E, $\tilde{E}$.

Experimental coverage (fixed target part)

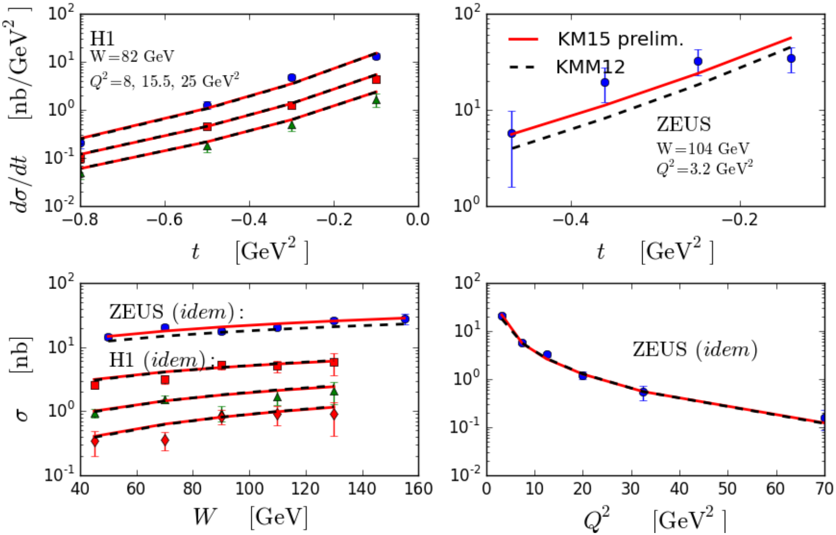
Collab.	Year	Observables	Kinematics			No. of points	
			x_B	Q^2 [GeV^2]	$\|t\|$ [GeV^2]	total	indep.
HERMES	2001	$A_{LU}^{\sin\phi}$	0.11	2.6	0.27	1	1
CLAS	2001	$A_{LU}^{\sin\phi}$	0.19	1.25	0.19	1	1
CLAS	2006	$A_{UL}^{\sin\phi}$	0.2–0.4	1.82	0.15–0.44	6	3
HERMES	2006	$A_{C}^{\cos\phi}$	0.08–0.12	2.0–3.7	0.03–0.42	4	4
Hall A	2006	$\sigma(\phi)$, $\Delta\sigma(\phi)$	0.36	1.5–2.3	0.17–0.33	4×24+12×24	4×24+12×24
CLAS	2007	$A_{LU}(\phi)$	0.11–0.58	1.0–4.8	0.09–1.8	62×12	62×12
HERMES	2008	$A_{C}^{\cos(0,1)\phi}$, $A_{UT,DVCS}^{\sin(\phi-\phi_S)}$, $A_{UT,I}^{\sin(\phi-\phi_S)\cos(0,1)\phi}$, $A_{UT,I}^{\cos(\phi-\phi_S)\sin\phi}$	0.03–0.35	1–10	<0.7	*12*+12+12 12+12 *12*	*4*+4+4 4+4 *4*
CLAS	2008	$A_{LU}(\phi)$	0.12–0.48	1.0–2.8	0.1–0.8	66	33
HERMES	2009	$A_{LU,I}^{\sin(1,2)\phi}$, $A_{LU,DVCS}^{\sin\phi}$, $A_{C}^{\cos(0,1,2,3)\phi}$	0.05–0.24	1.2–5.75	<0.7	18+18+18 18+18+*18*+*18*	6+6+6 6+6+*6*+*6*
HERMES	2010	$A_{UL}^{\sin(1,2,3)\phi}$, $A_{LL}^{\cos(0,1,2)\phi}$	0.03–0.35	1–10	<0.7	12+12+*12* 12+*12*+12	4+4+*4* 4+*4*+4
HERMES	2011	$A_{LT,I}^{\cos(\phi-\phi_S)\cos(0,1,2)\phi}$, $A_{LT,I}^{\sin(\phi-\phi_S)\sin(1,2)\phi}$, $A_{LT,BH+DVCS}^{\cos(\phi-\phi_S)\cos(0,1)\phi}$, $A_{LT,BH+DVCS}^{\sin(\phi-\phi_S)\sin\phi}$	0.03–0.35	1–10	<0.7	*12*+*12*+*12* *12*+*12* *12*+12 12	*4*+*4*+*4* *4*+*4* *4*+4 4
HERMES	2012	$A_{LU,I}^{\sin(1,2)\phi}$, $A_{LU,DVCS}^{\sin\phi}$, $A_{C}^{\cos(0,1,2,3)\phi}$	0.03–0.35	1–10	<0.7	18+*18*+*18* 18+18+*18*+*18*	6+*6*+*6* 6+6+*6*+*6*
CLAS	2015	$A_{LU}(\phi)$, $A_{UL}(\phi)$, $A_{LL}(\phi)$	0.17–0.47	1.3–3.5	0.1–1.4	166+166+166	166+166+166
CLAS	2015	$\sigma(\phi)$, $\Delta\sigma(\phi)$	0.1–0.58	1–4.6	0.09–0.52	2640+2640	2640+2640
Hall A	2015	$\sigma(\phi)$, $\Delta\sigma(\phi)$	0.33–0.40	1.5–2.6	0.17–0.37	480+600	240+360

Progression of fits over the years

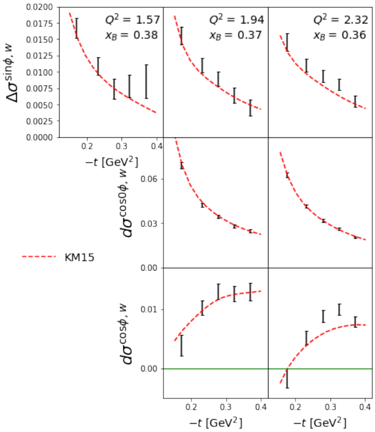
Model	KM09a	KM09b	KM10	KM10a	KM10b	KMS11	KMM12	KM15
free params.	{3}+(3)+5	{3}+(3)+6	{3}+15	{3}+10	{3}+15	NNet	{3}+15	{3}+15
χ^2/d.o.f.	32.0/31	33.4/34	135.7/160	129.2/149	115.5/126	13.8/36	123.5/80	240./275
F_2	{85}	{85}	{85}	{85}	{85}		{85}	{85}
$\sigma_{\rm DVCS}$	(45)	(45)	51	51	45		11	11
$d\sigma_{\rm DVCS}/dt$	(56)	(56)	56	56	56		24	24
$A_{LU}^{\sin\phi}$	12+12	12+12	12	16	12+12		4	13
$A_{LU,I}^{\sin\phi}$			18	18		18	6	6
$A_{C}^{\cos 0\phi}$							6	6
$A_{C}^{\cos\phi}$	12	12	18	18	12	18	6	6
$\Delta\sigma^{\sin\phi,w}$			12				12	63
$\sigma^{\cos 0\phi,w}$			4				4	58
$\sigma^{\cos\phi,w}$			4				4	58
$\sigma^{\cos\phi,w}/\sigma^{\cos 0\phi,w}$		4			4			
$A_{UL}^{\sin\phi}$							10	17
$A_{LL}^{\cos 0\phi}$							4	14
$A_{LL}^{\cos\phi}$								10
$A_{UT,I}^{\sin(\phi-\phi_S)\cos\phi}$							4	4

- [K.K., Müller, et al. '09–'15]
- These models are publicly available (google for "gpd page")

Fit examples (1/2): H1/ZEUS

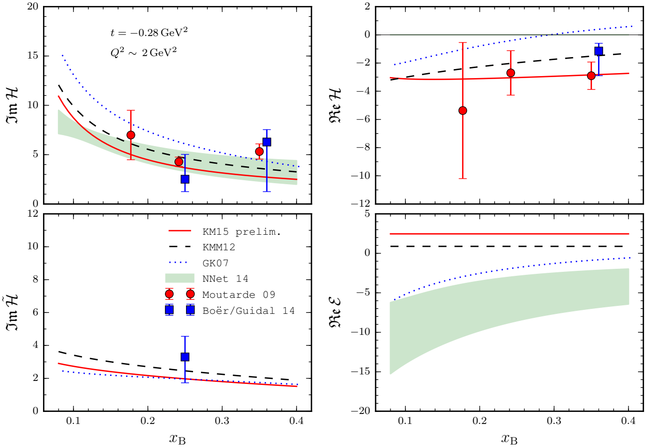


Fit examples (2/2): JLab's Hall A (2015)



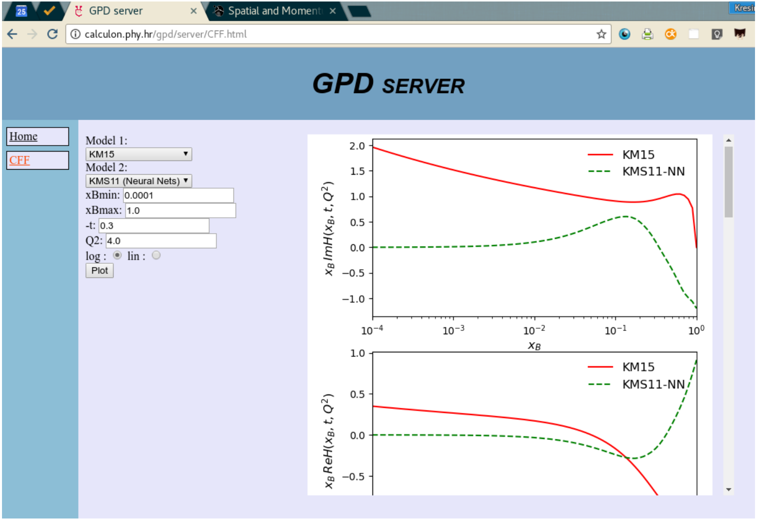
- KM15 global fit is fine. $\chi^2/n_{\rm d.o.f.} = 240./275$ ✓

CFFs from various fits



(from [K.K., Moutarde and Liuti '16])

GPD/CFF server



- Plots of all CFFs available; numerical values soon to come . . .

Accessing D-term

D-term

Matrix element of energy-momentum tensor $(a = q, g)$:

$$\langle P_2 | T^a_{\mu\nu} | P_1 \rangle = \bar{U}(P_2) \Big[A^a(t) \frac{\gamma_{(\mu} P_{\nu)}}{2} + B^a(t) \frac{i P_{(\mu} \sigma_{\nu)\rho} \Delta^\rho}{4M} + d_1^a(t) \frac{\Delta_\mu \Delta_\nu - g_{\mu\nu} \Delta^2}{5M} \pm \tilde{c}^a(t) g_{\mu\nu} \Big] U(P_1)$$

- $d_1^a(0)$ — unknown intrinsic property of particle (On par with mass or spin. Related to pressure distribution. [Polyakov '03])

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$$\int dx\, x\, H^q(x, \eta, t) = A^q(t) + \frac{4}{5} \eta^2 d^q_1(0)$$

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$$\int dx\, x\, H^q(x, \eta, t) = A^q(t) + \frac{4}{5} \eta^2 d_1^q(0)$$

- d_1^a appears also in dispersion relations for DVCS form factors:

D-term: models, lattice, phenomenology

$$\Re\mathfrak{e}\, \mathcal{H}(\xi, t) = \frac{1}{\pi} P.V. \int_0^1 dx \left(\frac{1}{\xi - x} - \frac{1}{\xi + x} \right) \Im\mathfrak{m}\, \mathcal{H}(x, t) + \Delta(t)$$

$$\Delta(t) = 4 \sum_q Q_q^2 (d_1^q(t) + d_3^q(t) + \cdots)$$

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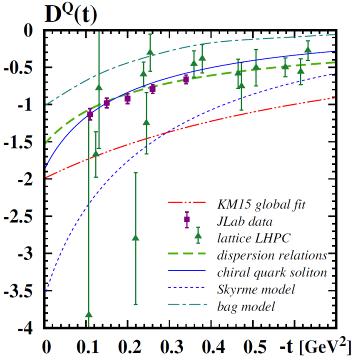
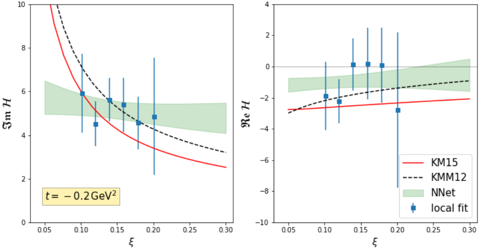


[M. Polyakov, P. Schweitzer '18]

Local fit to just CLAS σ and $\Delta\sigma$

- Two parameters: $\mathfrak{Im}\,\mathcal{H}$, $\mathfrak{Re}\,\mathcal{H}$. Other CFFs are zero.



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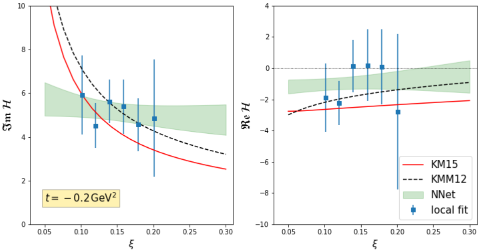
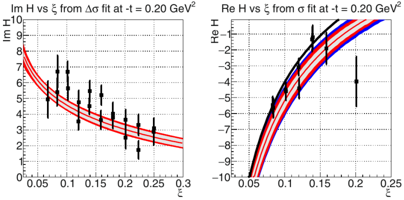
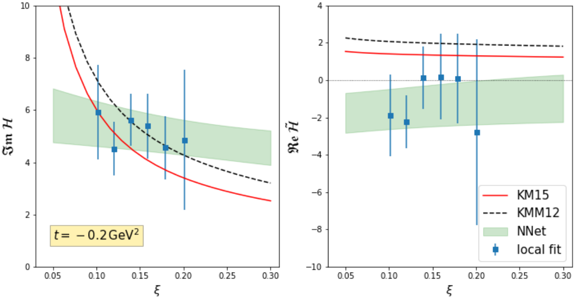


[V. Burkert, L. Eloudrhiri, F.-X. Girod '18]



Alternative model: $\mathfrak{Im}\,\mathcal{H}$, $\mathfrak{Re}\,\mathcal{H} \to \mathfrak{Im}\,\mathcal{H}$, $\mathfrak{Re}\,\tilde{\mathcal{H}}$



- Works just as well.

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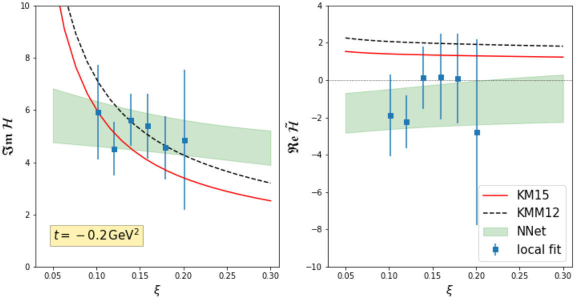

- Works just as well.
- Setting D-term to zero also works well for CLAS data alone

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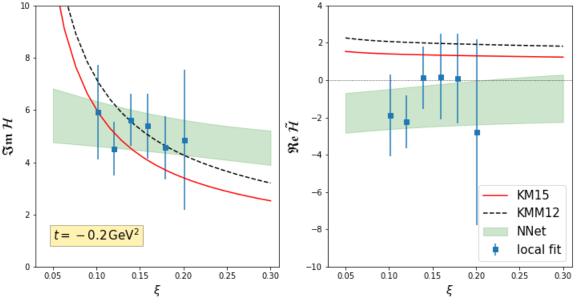
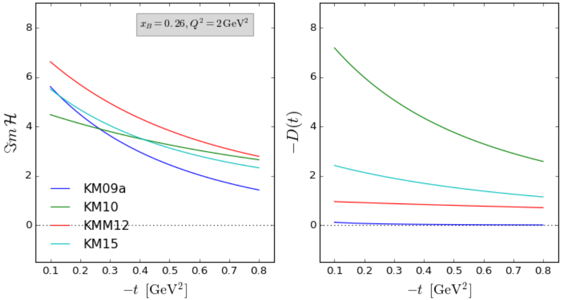


- Works just as well.
- Setting D-term to zero also works well for CLAS data alone
- We should use all available data — global fits

D-term in global fits over the years



- Better constraint on D-term: measurement of beam charge asymmetry, double DVCS, . . .

Higher twists?

Including higher twists

- Definition of Compton form factors to given twist is convention dependent (e.g. choice of $(n,\tilde{n})$—longitudinal plane)
- BMJ [Belitsky, Müller, Ji]: $\mathcal{H}_{++}$, $\mathcal{E}_{++}$, ..., $\mathcal{H}_{0+}$, $\mathcal{E}_{0+}$, ...,
- BMP [Braun, Manashov, Pirnay]: $\underbrace{\mathbb{H}_{++}, \mathbb{E}_{++}}_{\text{twist-2} + \cdots}, \ldots \mathbb{H}_{0+}, \mathbb{E}_{0+}, \ldots,$
- Lorentz transformation from BMP to BMJ frame:

$$\mathcal{H}_{++} = \mathbb{H}_{++} + \frac{\chi}{2}(\mathbb{H}_{++} + \mathbb{H}_{-+}) - \chi_0 \mathbb{H}_{0+}$$
$$\mathcal{H}_{0+} = -(1+\chi)\mathbb{H}_{0+} + \chi_0(\mathbb{H}_{++} + \mathbb{H}_{-+})$$

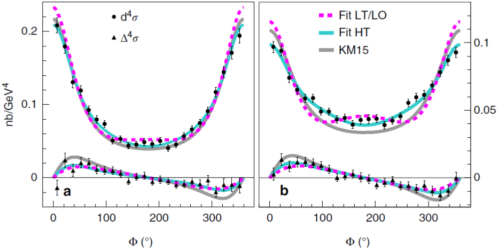
collects most of the HT effects.

$$\chi_0 \sim \mathcal{O}\left(\frac{1}{Q}\right) , \quad \chi \sim \mathcal{O}\left(\frac{1}{Q^2}\right)$$

Leading (LT) vs. higher twist (HT) models

- JLab's Hall A performed fits to their 2017 data using BMP conventions (separate fit for each t-bin):

LT/LO	$\mathbb{H}_{++}$, $\mathbb{E}_{++}$, $\tilde{\mathbb{H}}_{++}$, $\tilde{\mathbb{E}}_{++}$	✗ bad fit
HT	$\mathbb{H}_{++}$, $\mathbb{H}_{0+}$, $\tilde{\mathbb{H}}_{++}$, $\tilde{\mathbb{H}}_{0+}$	✓ good fit
NLO	$\mathbb{H}_{++}$, $\mathbb{H}_{-+}$, $\tilde{\mathbb{H}}_{++}$, $\tilde{\mathbb{H}}_{-+}$	✓ good fit



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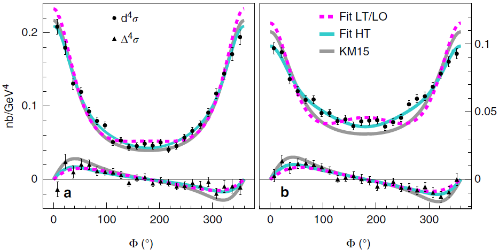


- Hall A conclusion: "We glimpse gluons here!" (at $x_B = 0.36$)

LT vs. HT: chi-squares

- $n_{\mathrm{d.o.f.}} = 208 \pm 2$

Hall A:

	BMP ($\mathbb{F}$)		
t/GeV^2	LO/LT	HT	NLO
-0.18	250 ✗	204 ✓	206 ✓
-0.24	367 ✗	206 ✓	208 ✓
-0.30	415 ✗	189 ✓	190 ✓

LT vs. HT: chi-squares

- $n_{\mathrm{d.o.f.}} = 208 \pm 2$

Hall A:

	BMP ($\mathbb{F}$)		
t/GeV^2	LO/LT	HT	NLO
-0.18	250 ✗	204 ✓	206 ✓
-0.24	367 ✗	206 ✓	208 ✓
-0.30	415 ✗	189 ✓	190 ✓

This work:

	BMP ($\mathbb{F}$)		
t/GeV^2	LO/LT	HT	NLO
-0.18	231 ✗	204 ✓	N/A
-0.24	254 ✗	199 ✓	N/A
-0.30	229 ✗	180 ✓	N/A

LT vs. HT: chi-squares

- $n_{\mathrm{d.o.f.}} = 208 \pm 2$

Hall A:

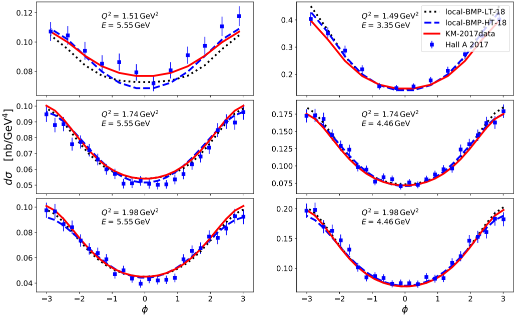
	BMP ($\mathbb{F}$)		
t/GeV^2	LO/LT	HT	NLO
-0.18	250 ✗	204 ✓	206 ✓
-0.24	367 ✗	206 ✓	208 ✓
-0.30	415 ✗	189 ✓	190 ✓

This work:

	BMP ($\mathbb{F}$)			BMJ ($\mathcal{F}$)
t/GeV^2	LO/LT	HT	NLO	LT (KM)
-0.18	231 ✗	204 ✓	N/A	213 ✓
-0.24	254 ✗	199 ✓	N/A	210 ✓
-0.30	229 ✗	180 ✓	N/A	213 ✓

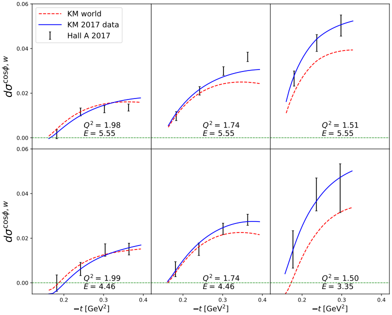
Hall A 2017 $d\sigma$

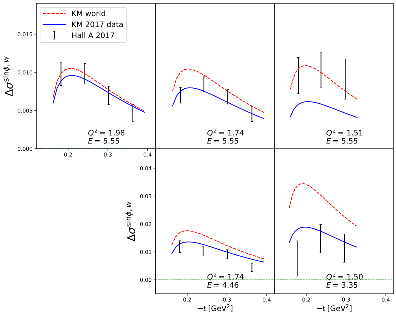
- $t = -0.18\,\mathrm{GeV}^2$



- Conclusion: Hall A 2017 data alone can be satisfactory described within twist-2 framework

Including Hall A 2017 data in global world fit: fail ✗



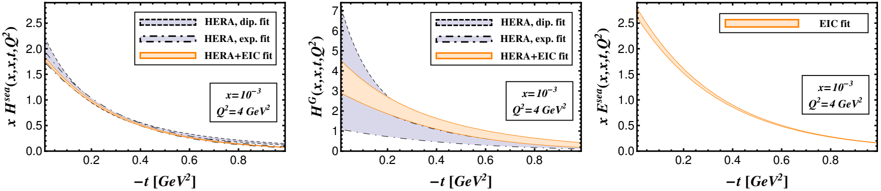


Global world DVCS data fit

before 2017	including 2017 Hall A
$\chi^2/n_{\rm d.o.f} = 240./275$ ✓	$\chi^2/n_{\rm d.o.f} = 545./337$ ✗

DVCS at EIC

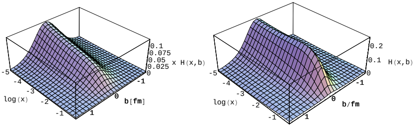
- Future polarized electron-ion collider (EIC) will provide unique insight into sea GPDs.
- [Aschenauer, Fazio, K.K., Müller '13] fit to simulated DVCS data at 20 GeV $\times$ 250 GeV taking $E_{\rm sea}(x, \eta, t) = \kappa_{\rm sea} H_{\rm sea}(x, \eta, t)$



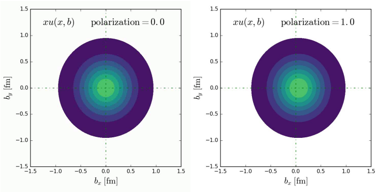
- Improved knowledge of low-t quark and gluon GPDs H ($\Longrightarrow$ 3D parton imaging)
- Improved knowledge of sea quark GPD E

Tomography

- Quark and gluon sea 2D distributions $H(x, \vec{b}_\perp)$ ([KM] model)



- Sivers effect for valence quarks ([GK] model)



- See also [Dupré, Guidal, Vanderhaeghen '16]
- Tomography is still very much model-dependent; e.g. some extrapolation from $H(x, x, t)$ to $H(x, 0, t)$ is needed.

Summary

- Global fits of all proton DVCS data using flexible hybrid models were in healthy shape until 2017
- Standard global model fitting and neural networks approach are complementing each other
- First steps are made towards extracting the D-term
- Inclusion of higher twist effects is likely important for interpretation of new JLab data, but maybe not for quality of description of this data
- New Hall A 2017 data present a challenge

Summary

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The End