Multichannel GPD extraction at LO and NLO at high energy

Marija Čuić
with prof. Krešimir Kumerički

University of Zagreb, Croatia

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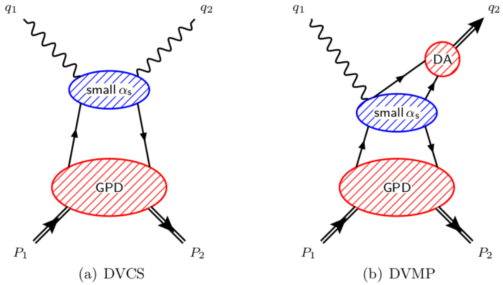
Outline

Accessing GPDs

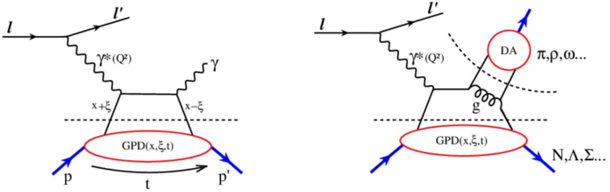
- exclusive processes such as DVCS and DVMP



- at leading twist four complex Compton form factors $\mathcal{H}\left(\xi,t,Q^2\right)$, $\mathcal{E}\left(\xi,t,Q^2\right)$, $\widetilde{\mathcal{H}}\left(\xi,t,Q^2\right)$, $\widetilde{\mathcal{E}}\left(\xi,t,Q^2\right)$
- we can test universality of GPDs and obtain flavour separation

Factorization and GPDs

- factorization theorem [Collins et al. '97]
- DVCS: transversal photon, DVMP: longitudinal photon and meson at twist-2



- CFFs and TFFs are a convolution [Müller '92, et al. '94, Ji, Radyushkin '96]

$$\text{DVCS: } \mathcal{F}^q\left(\xi,\Delta^2,\mathcal{Q}^2\right) = \int_{-1}^{1}\frac{\mathrm{d}x}{2\xi}\left[\frac{2(\xi-i\epsilon)}{\xi-x-i\epsilon}-\frac{2(\xi-i\epsilon)}{\xi+x-i\epsilon}\right]\underbrace{F^q\left(x,\eta=\xi,t\right)}_{\text{GPD}}$$

$$\text{DVMP: } \mathcal{F}_M^q\left(\xi,\Delta^2,\mathcal{Q}^2\right) = \frac{f_M C_{\mathrm{F}}}{\mathcal{Q}N_{\mathrm{c}}}\int_{-1}^{1}\frac{\mathrm{d}x}{2\xi}\int_0^1 \mathrm{d}v\,\underbrace{\varphi_M(v)^{\mathrm{q}}}_{\text{DA}}\,T^{(0)}\left(x,\xi,v\right)\underbrace{F^q(x,\eta=\xi,t)}_{\text{GPD}}$$

Modelling GPDs

GPD evolution

- evolution in x space complicated, we use conformal moments

$$F_n(\eta, t) = \int_{-1}^{1} dx c_n(x, \eta) F(x, \eta, t)$$

$$c_n(x, \eta) = \eta^n \frac{\Gamma\left(\frac{3}{2}\right)\Gamma(1+n)}{2^n \Gamma\left(\frac{3}{2}+n\right)} C_n^{\frac{3}{2}}\left(\frac{x}{\eta}\right)$$

- $C_n^{3/2}$ Gegenbauer polynomials for quarks (5/2 for gluons)
- analytic continuation $n \to j \in \mathbb{C}$
- evolution diagonal in j space at LO

$$\mu \frac{d}{d\mu} F_j^q\left(\eta, t, \mu^2\right) = -\frac{\alpha_s(\mu)}{2\pi} \gamma_j^{(0)} F_j^q\left(\eta, t^2, \mu^2\right)$$

Valence quark GPDs

- valence quarks modelled in x space ($q = u, d$) at crossover line $x = \eta$ (no Q^2 evolution)

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

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

$$\alpha_v(t) = 0.43 + 0.85 t/\mathrm{GeV}^2$$

- fixed parameters: n from PDFs, $\alpha(t)$ Regge trajectory, p counting rules

Sea quark and gluon GPDs

- sea quarks modelled in j space
- $SO(3)$ partial waves expansion

$$F_j(\eta,t) = \sum_{\substack{J=J_{\min} \\ \text{even}}}^{j+1} F_j^J(t)\eta^{j+1-J}\hat{d}^J_{\alpha,\beta}(\eta), \quad J = j+1, j-1, j-3, \ldots$$

- leading contribution

$$H_j^a(\eta=0,t) = N^a \frac{\mathrm{B}\left(1-\alpha^a+j, \beta^a+1\right)}{\mathrm{B}\left(2-\alpha^a, \beta^a+1\right)} \frac{\beta(t)}{1-\dfrac{t}{\left(m_j^a\right)^2}},$$

$$\left(m_j^a\right)^2 = \frac{1+j-\alpha^a}{\alpha'^a}, \quad \beta(t) = \left(1-\frac{t}{M^2}\right)^{-p}, \quad a = \{s, g\}$$

- full NLO QCD Q^2 evolution

- partial wave expansion implemented simply in Mellin-Barnes integral

$$\boldsymbol{\mathcal{H}} = \frac{1}{2i}\int_{c-i\infty}^{c+i\infty} dj \xi^{-j-1}\left[i + \tan\left(\frac{\pi j}{2}\right)\right] \times$$
$$\times\left[[\mathbb{C}\otimes\mathbb{E}]_j + [\mathbb{C}\otimes\mathbb{E}]_{j+2}\boldsymbol{S} + [\mathbb{C}\otimes\mathbb{E}]_{j+4}\boldsymbol{T}\right]\boldsymbol{H}_j^{(l)}$$

- 10-15 parameters

Dispersion relations

- CFFs constrained by dispersion relations

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

- subtraction constant model

$$\Delta(t) = \frac{C}{\left(1 - \frac{t}{M_C^2}\right)^2}$$

- $\Delta_{\mathcal{H}}(t) = -\Delta_{\mathcal{E}}(t)$, $\Delta_{\tilde{\mathcal{H}}}(t) = \Delta_{\tilde{\mathcal{E}}}(t) = 0$
- only imaginary part of CFFs and one subtraction constant $\Delta(t)$ are modelled

Results

NLO DIS+DVCS+DVMP small-x global fit

- First global fits to DIS+DVCS+DVMP HERA collider data [Lautenschlager, Müller, Schäfer, '13, unpublished!]
- hard scattering amplitude corrected in the meantime [Duplančić, Müller, Passek-Kumerički '17]
- [M. Č. et al., '23] preliminary results for NLO DIS+DVCS+DVMP small-x global fit
- we also studied LO fits, fits to DIS+DVCS and fits to DIS+DVMP
- what are the effects of NLO corrections?
- can we get universal GPDs regardless of DVCS and DVMP data?

Cross sections

- DVCS

$$\frac{d\sigma^{\gamma^* N \to \gamma N}}{d\Delta^2} \approx \frac{\pi \alpha_{em}^2}{(W^2 + \mathcal{Q}^2)^2} \left[|\mathcal{H}|^2 + |\widetilde{\mathcal{H}}|^2 - \frac{\Delta^2}{4M^2} |\mathcal{E}|^2 \right]$$

- DVMP

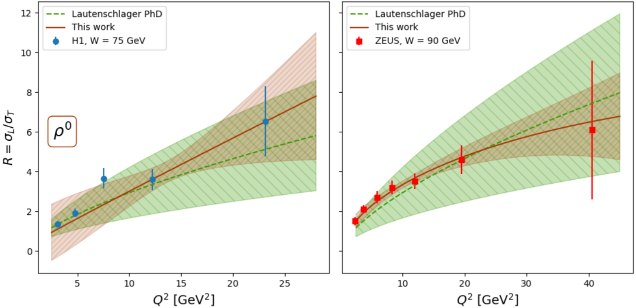
$$\frac{d\sigma^{\gamma^* N \to V N}}{d\Delta^2} \approx \frac{4\pi^2 \alpha_{em} x_B^2}{\mathcal{Q}^4} \left[|\mathcal{H}|^2 - \frac{\Delta^2}{4M^2} |\mathcal{E}|^2 \right]$$

- for $|\Delta^2| < 1$ GeV^2 CFF $\mathcal{E}$ suppressed by $-\frac{\langle \Delta^2 \rangle}{4M^2} \approx 5 \times 10^{-2}$
- for $\widetilde{\mathcal{H}}$ Regge intercept $\alpha(0) \approx 1/2$, for $\mathcal{H}$ $\alpha(0) \approx 1$, $\widetilde{\mathcal{H}}$ also suppressed
- we ignore valence contributions, only singlet $\mathcal{H}$
- asymptotic distribution amplitude, dominant term in conformal space $\varphi_0 \approx 1$

Changes to original analysis

- for DVMP cut-off at $Q^2 \geq 10$ GeV^2 insetad of 4
- no ϕ production
- different parameter constraints
- Q^2 and W dependence in $R = \sigma_L/\sigma_T$

$$R\left(Q^2\right) = \frac{Q^2}{m_V^2}\left(1 + a\frac{Q^2}{m_V^2}\right)^{-p} \rightarrow R(W, Q^2) = \frac{Q^2}{m_\rho^2}\left(1 + a\frac{Q^2}{m_\rho^2}\right)^{-p}\left(1 - b\frac{Q^2}{W}\right)$$



Data & χ^2/N_{pts}

- DIS data: H1 F_2
- DVCS: H1 and ZEUS data, $Q^2 \geq 5.0$ GeV^2
- DVMP: H1 nd ZEUS ρ^0 production, $Q^2 \geq 10.0$ GeV^2
- no t dependence

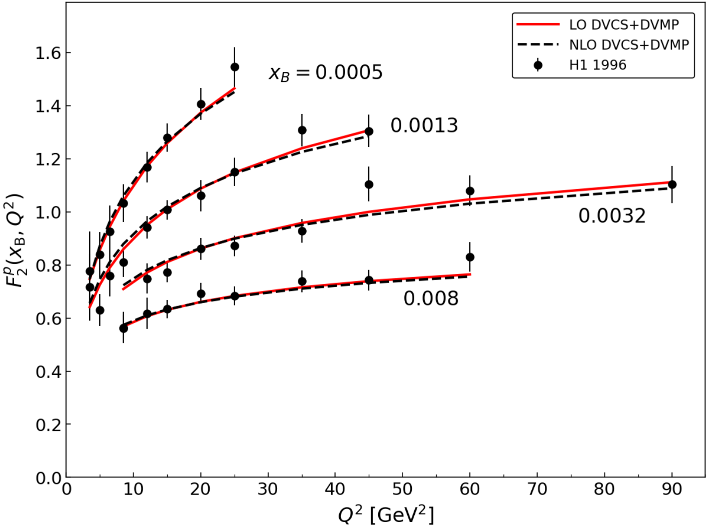
Dataset	N_{pts}	LO DVCS	LO DVMP	LO ALL	NLO DVCS	NLO DVMP	NLO ALL
DIS	85	0.6	0.6	0.6	0.8	0.8	0.8
DVCS	27	0.4	12252.2	0.6	0.6	27269.6	0.8
DVMP	45	49.7	3.1	3.3	11.7	1.5	1.7
Total	157	14.6	2108.3	1.4	3.9	4690.6	1.1

Parameters

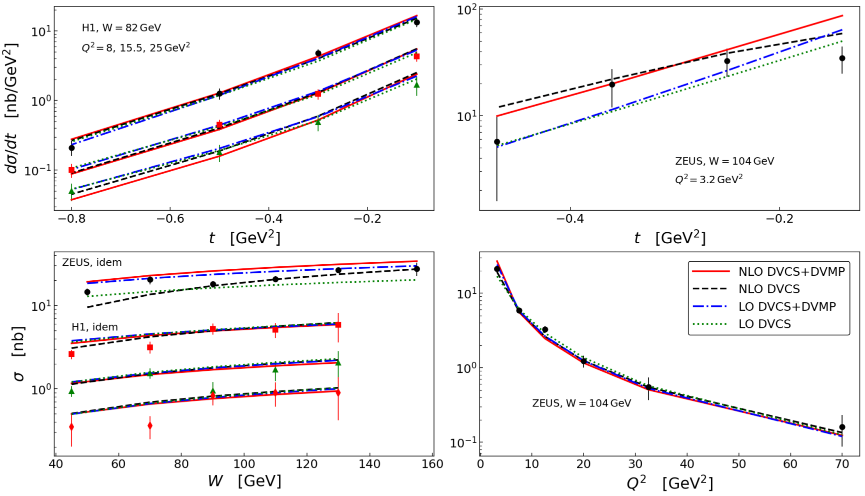
- pure DVMP fits prefer large quark skewness, rely on cancelation from gluons
- subleading waves were larger than leading ones, unstable
- DVMP more sensitive to gluons, we leave more freedom to gluon subleading PWs
- we want a decrease in contribution for PW expansion

	n^{sea}	α_0^{sea}	α'_{sea}	m_{sea}^2	s_2^{sea}	s_4^{sea}	α_0^G	α'_G	m_G^2	s_2^G	s_4^G
unit		1	GeV^{-2}	GeV^2	1	1	1	GeV^{-2}	GeV^2	1	1
initial	0.15	1.00	0.15	0.70	-0.20	0.00	1.00	0.15	0.70	0.00	0.00
limits			(0.0,1.0)	(0,3)	(-0.3,0.3)	(-0.1,0.1)		(0.0,1.0)	(0,3)	(-3.0,3.0)	(-1.0,1.0)
final	0.168	1.128	0.125	0.412	0.280	-0.044	1.099	0.000	0.145	2.958	-0.951
uncert.	0.002	0.011	0.040	0.050	0.032	0.010	0.011	0.010	0.008	0.039	0.025

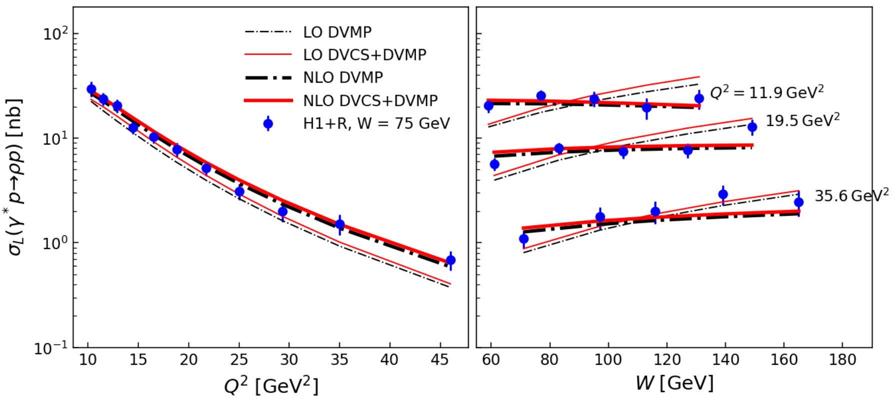
DIS F_2 data description

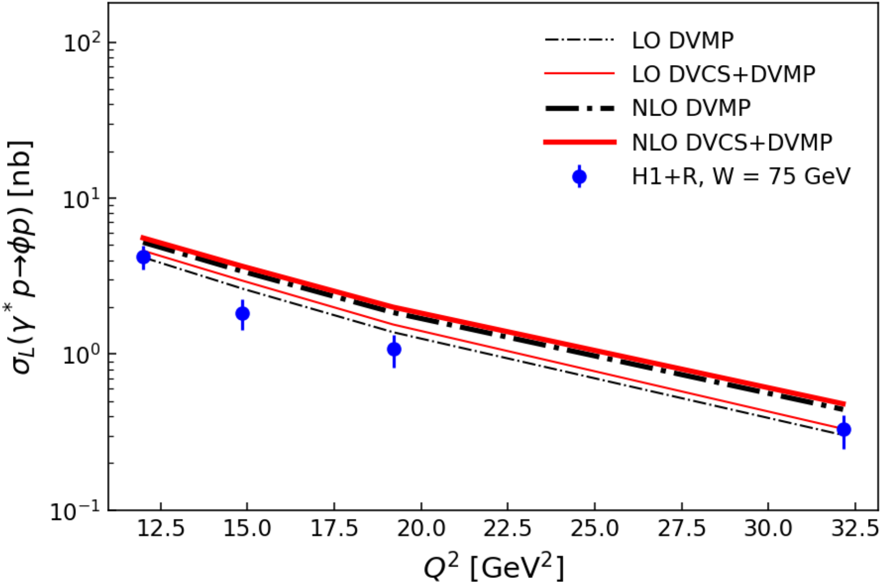


DVCS data description

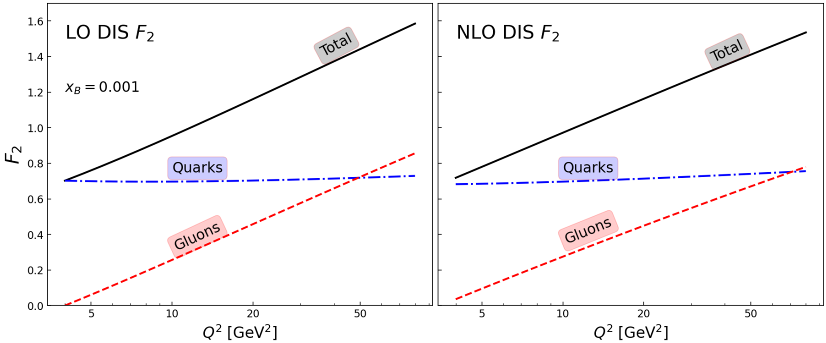


DVMP data description



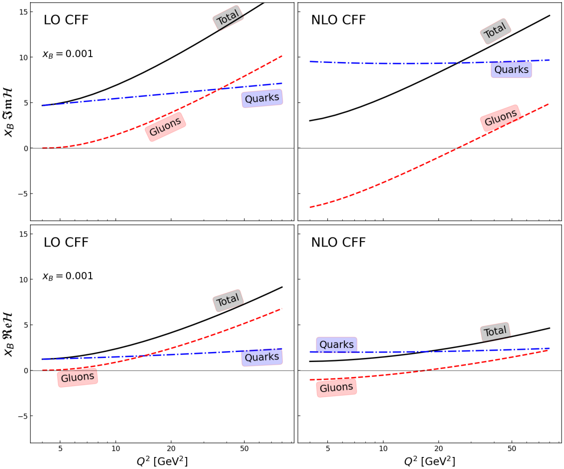

LO DVMP
LO DVCS+DVMP
NLO DVMP
NLO DVCS+DVMP
H1+R, W = 75 GeV
$\sigma_L(\gamma^* p \to \phi p)$ [nb]
Q^2 [GeV^2]
10^2
10^1
10^0
10^{-1}
12.5
15.0
17.5
20.0
22.5
25.0
27.5
30.0
32.5

Quark and gluon contributions: DIS



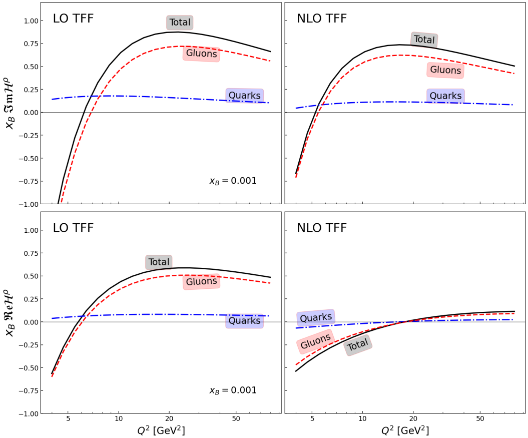
- at LO gluons do not contribute at low Q^2
- not much changes at NLO

Quark and gluon contributions: DVCS



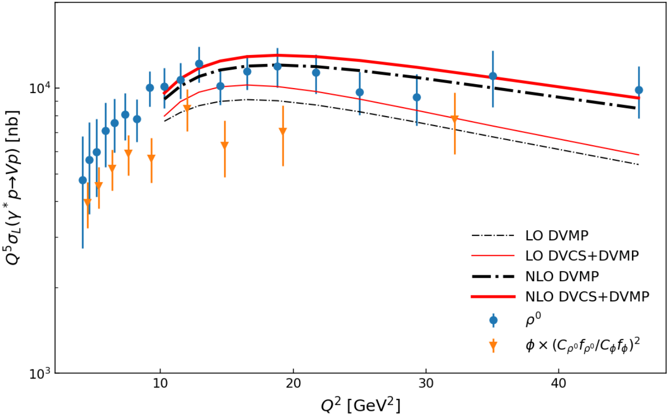
- at LO gluons do not contribute at low Q^2
- at NLO gluons negative at low Q^2

Quark and gluon contributions: DVMP



- at LO gluons dominate at low Q^2
- at NLO a much different story, gluons negative at low Q^2, dominate at large Q^2

DVMP Q^2 scalling

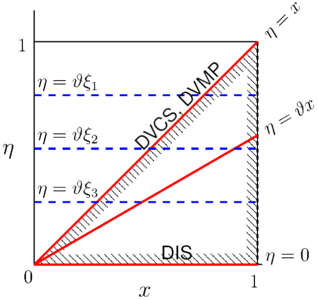


- theory scales roughly as Q^5 after $\sim$10 GeV^2

Skewness

- skewness: ratio of GPD to corresponding PDF

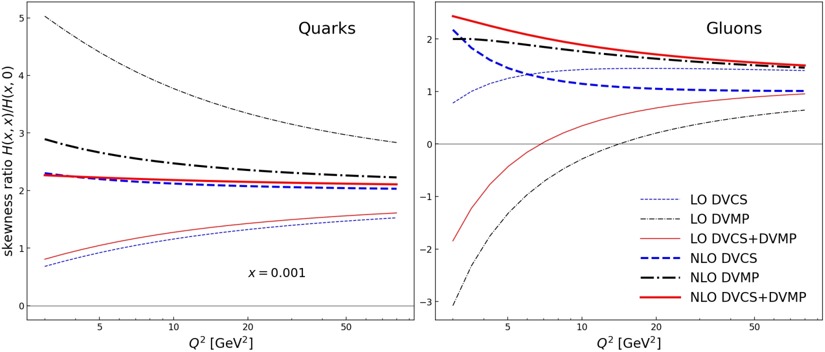
$$r = \frac{H(x, \eta = x)}{q(x)}$$



- conformal (Shuvaev) values, PDFs completely specify GPDs:

$$r^q \approx 1.65, \quad r^G \approx 1$$

Skewness at LO and NLO



Universal GPD structure emerges at NLO!

Conclusion

- stable fits for higher Q^2 and careful L-T separation
- Q^5 scaling after $Q^2 \approx 10$ GeV^2
- universal GPD structure emerges at NLO