CFF and GPD extraction from multi-channel fits

Marija Čuić

with prof. Krešimir Kumerički

University of Zagreb, Croatia

International Workshop on Hadron Structure and Spectroscopy 2023

Jun 25 – 28, 2023, CTU, Prague

Outline

1. Introduction
2. Modelling
3. Results
    - CFF extraction
    - Flavor separation
    - DIS+DVCS+DVMP

Accessing GPDs

- exclusive processes such as DVCS, DVMP, timelike DVCS, double DVCS, diphoton production ...
- at leading order and twist-2 four complex Compton form factors $\mathcal{H}\left(\xi,t,Q^2\right), \mathcal{E}\left(\xi,t,Q^2\right), \widetilde{\mathcal{H}}\left(\xi,t,Q^2\right), \widetilde{\mathcal{E}}\left(\xi,t,Q^2\right)$

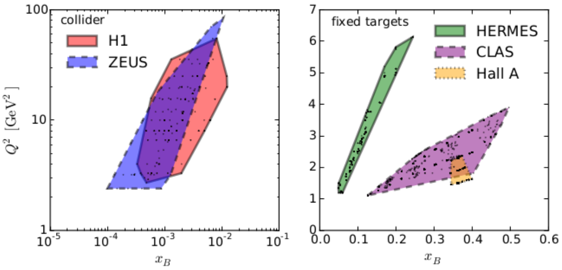
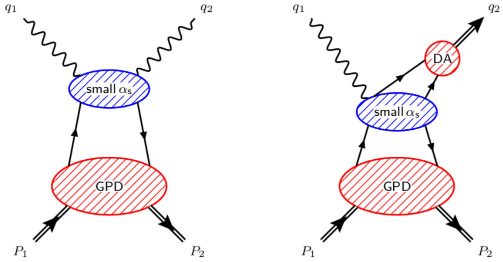


Figure: Experimental coverage

- factorization theorem [Collins et al. '98]



(a) DVCS (b) DVMP

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

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

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

Types of models

1. "Physical" GPD (and CFF) model
2. Neural network parametrization of CFFs (no GPD extraction)

Modelling GPDs

GPD evolution

- evolution in x space complicated, we use conformal moments

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

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

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

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

Hybrid model

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

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

- sea quarks and gluons modelled in j space
- $SO(3)$ partial waves expansion
- leading contribution

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

- dipole $t-$dependence
- full NLO QCD Q^2 evolution

Dispersion relations

- CFFs constrained by dispersion relations

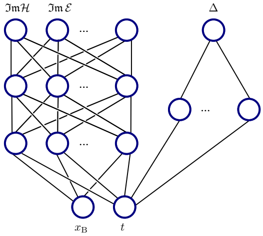
$$\mathfrak{Re}\,\mathcal{H}(\xi,t) \stackrel{LO}{=} \Delta(t)+\frac{1}{\pi}\mathrm{P.V.}\int_0^1 \mathrm{d}x \left(\frac{1}{\xi-x}-\frac{1}{\xi+x}\right)\mathfrak{Im}\,\mathcal{H}(x,t)$$

- only imaginary part of CFFs and one subtraction constant $\Delta(t)$ are modelled

  - for physical models

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

  - for neural nets



Results

Models

- physical models: KM, neural nets models: NN, dispersion relation constrained neural nets models: NNDR
- separate model for each flavor CFF: $\mathcal{H}_u$, $\mathcal{H}_d$, $\mathcal{E}_u$, $\mathcal{E}_d$
- using isospin symmetry and a simple model $\mathcal{H} = \frac{4}{9}\mathcal{H}_u + \frac{1}{9}\mathcal{H}_d$ $\rightarrow$ flavoured models fKM, fNN, fNNDR

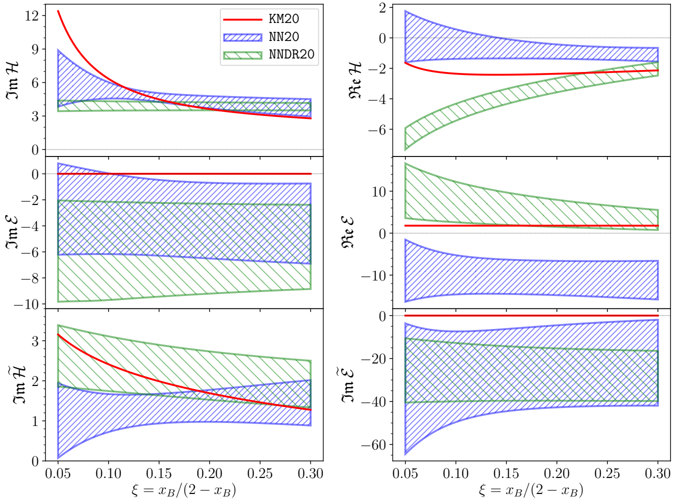
Observable	n_{pts}	KM20	NN20	NNDR20	fKM20	fNNDR20
# CFFs + Δs		3+1	6	4+1	5+2	8+2
Total (harmonics)	277	1.3	1.6	1.7	1.7	1.8
CLAS [19] A_{LU}	162	0.9	1.0	1.1	1.2	1.3
CLAS [19] A_{UL}	160	1.5	1.7	1.8	1.8	2.0
CLAS [19] A_{LL}	166	1.3	3.9	0.8	1.1	1.6
CLAS [20] $d\sigma$	1014	1.1	1.0	1.2	1.2	1.1
CLAS [20] $\Delta\sigma$	1012	0.9	0.9	1.0	0.9	1.1
Hall A [21] $d\sigma$	240	1.2	1.9	1.7	0.9	1.3
Hall A [21] $\Delta\sigma$	358	0.7	0.8	0.8	0.7	0.7
Hall A [22] $d\sigma$	450	1.5	1.6	1.7	1.9	2.0
Hall A [22] $\Delta\sigma$	360	1.6	2.2	2.2	1.9	1.7
Hall A [8] $d\sigma_n$	96				1.2	0.9
Total (ϕ-space)	4018	1.1	1.3	1.3	1.2	1.3

Table: χ^2/N_{pts} in 2020

2023:
CLAS 12 upgrade pDVCS and nDVCS BSA, 39 harmonics
χ^2/N_{pts}(fNN23) $= 1.25$
χ^2/N_{pts}(fNNDR23) > 3

Extraction of 6 CFFs 2020

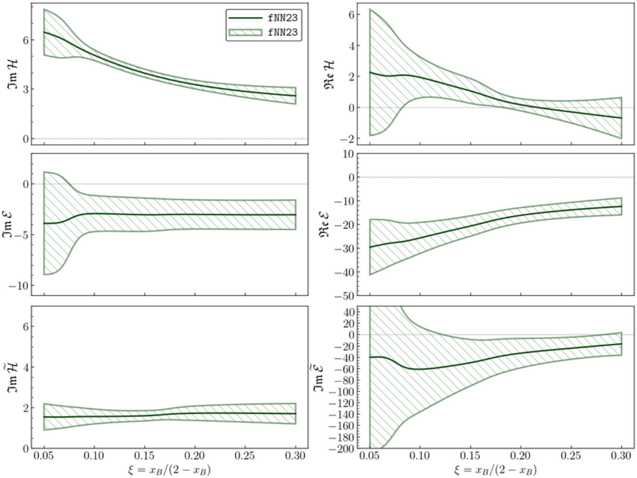
[M. Č., K. Kumerički, A. Schäfer, '20], JLab Hall A and CLAS data



$\mathcal{Q}^2 = 4$ GeV^2
$t = -0.2$ GeV^2

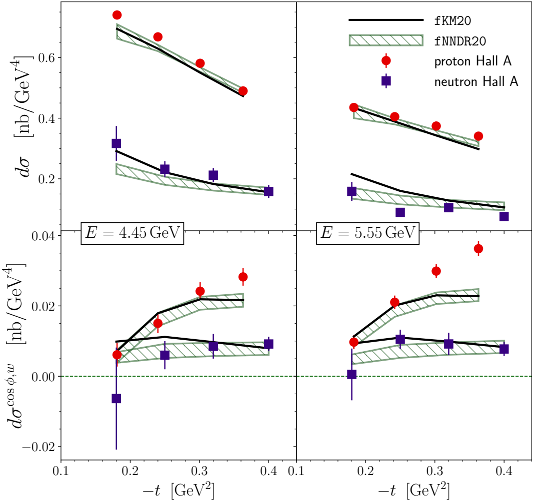
Extraction of 6 CFFs 2023

Preliminary CLAS proton and neutron DVCS BSA, S. Niccolai, A. Hobart, $E = 10.4$ GeV



$\mathcal{Q}^2 = 4$ GeV^2
$t = -0.2$ GeV^2

Hall A 2020 measurements



$x_B = 0.36$
$\mathcal{Q}^2 = 1.75\ \mathrm{GeV}^2$

Flavor separation of $\mathcal{H}$

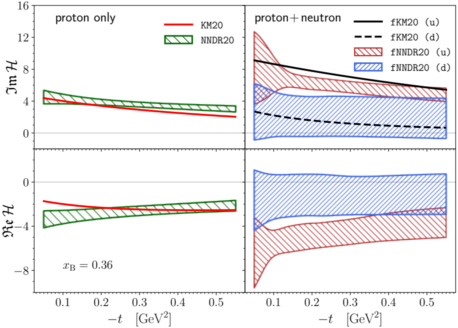


Figure: 2020 fits

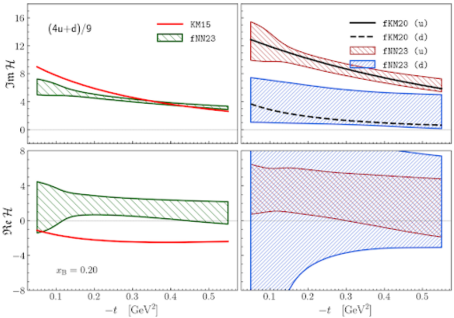


Figure: 2023 fits

Flavor separation of $\mathcal{E}$

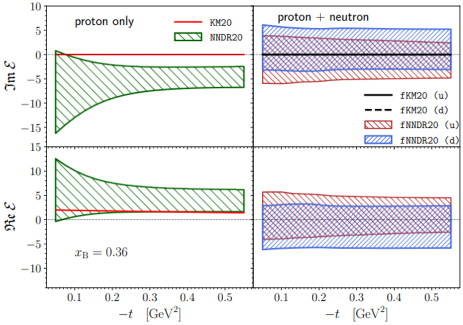


Figure: 2020 fits

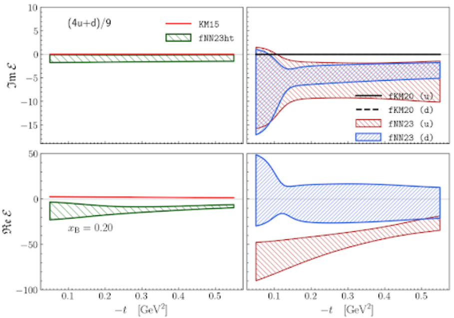


Figure: 2023 fits

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

- only considered sea quarks and gluons, full NLO Q^2 evolution

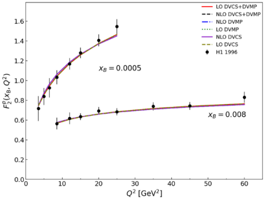
$$\frac{d\sigma^{\gamma_L^* N \to V_L^0 N'}}{d\Delta^2} \approx \frac{4\pi^2 \alpha_{\rm em} x_B^2}{\mathcal{Q}^4} |\mathcal{H}|^2$$

- H1 and ZEUS measurements of ρ^0 DVMP
- fit to HERA collider data (excluding t-dependent DVMP data): $\chi^2/n_{\text{d.o.f.}} = 172.45/146 \approx 1.2$
- what are the effects of NLO corrections?
- can we get universal GPDs regardless of DVCS and DVMP data?

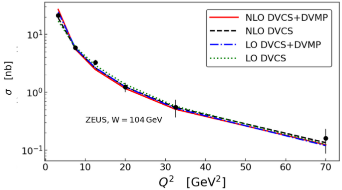
  $\Rightarrow$ we study LO fits, fits to DIS+DVCS and fits to DIS+DVMP

Data description

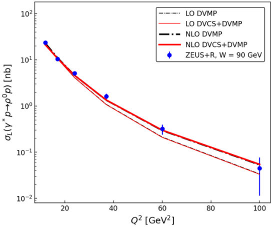
DIS

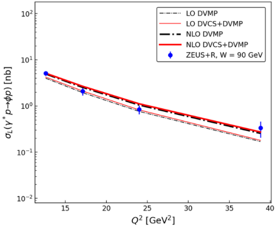


DVCS



DVMP





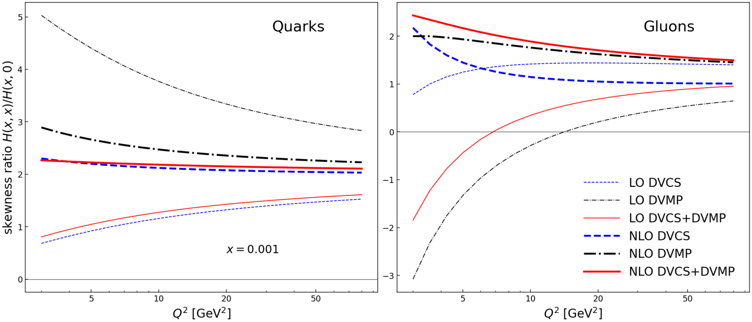
Skewness

- skewness: ratio of GPD to corresponding PDF

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

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

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



Conclusion

- extraction of 6 out of 8 CFFs
- CLAS 12 upgrade data disfavors DR models
- partial flavor separation of CFFs $\mathcal{H}$ and $\mathcal{E}$
- universal GPD structure emerges at NLO