

Exclusive production at large Q^2

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Introduction
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Modelling
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Results
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Future plans
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Outline

① Introduction

② Modelling

③ Results

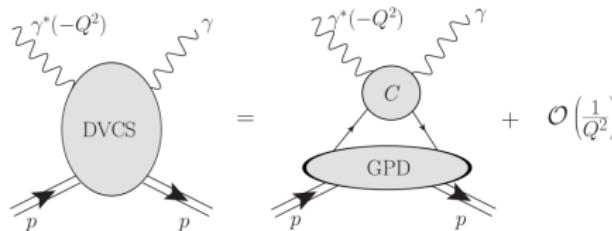
DVCS

DIS+DVCS+DVMP

④ Future plans

Accessing GPDs

- exclusive processes such as DVCS and DVMP
 - at leading order four complex Compton form factors
 $\mathcal{H}(\xi, t, Q^2), \mathcal{E}(\xi, t, Q^2), \tilde{\mathcal{H}}(\xi, t, Q^2), \tilde{\mathcal{E}}(\xi, t, Q^2)$
 - factorization theorem [Collins et al. '98]



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

$$^a\mathcal{H}(\xi, t, Q^2) = \int dx C^a \left(x, \xi, \frac{Q^2}{Q_0^2} \right) \underbrace{H^a(x, \eta = \xi, t, Q_0^2)}_{\text{GPD}}, \quad a = q, G$$

Types of models

- ① “Physical” GPD (and CFF) model
 - ② Neural network parametrization of CFFs

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Modelling GPDs

GPD evolution

- evolution in x space complicated, we introduce 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
 - analytic continuation $n \rightarrow j \in \mathbb{C}$
 - evolution diagonal in j space at LO

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

Valence quark GPDs

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

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

$$H(x, x, t) = nr2^\alpha \left(\frac{2x}{1+x}\right)^{-\alpha(t)} \left(\frac{1-x}{1+x}\right)^b \frac{1}{\left(1 - \frac{1-x}{1+x} \frac{t}{M^2}\right)^p}.$$

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

- 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

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

- leading contribution

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

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

- full NLO QCD Q^2 evolution

- partial wave expansion implemented simply in Mellin-Barnes integral

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

- 10-15 parameters

Cross sections

- ## • DVCS

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

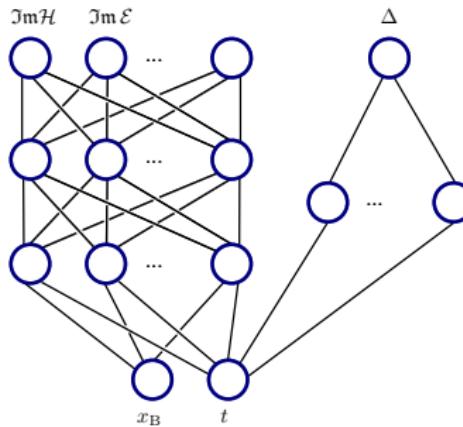
- ## DVMP

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

→ for $|\Delta^2| < 1 \text{ GeV}^2$ CFF \mathcal{E} suppressed by

$$-\frac{\langle \Delta^2 \rangle}{4M^2} \approx 5 \times 10^{-2}$$

→ for $\tilde{\mathcal{H}}$ Regge intercept $\alpha(0) \approx 1/2$, for \mathcal{H} $\alpha(0) \approx 1$, $\tilde{\mathcal{H}}$ also suppressed



- CFFs constrained by dispersion relations

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

- Only imaginary part of CFFs and one subtraction constant $\Delta(t)$ are parametrized by neural nets

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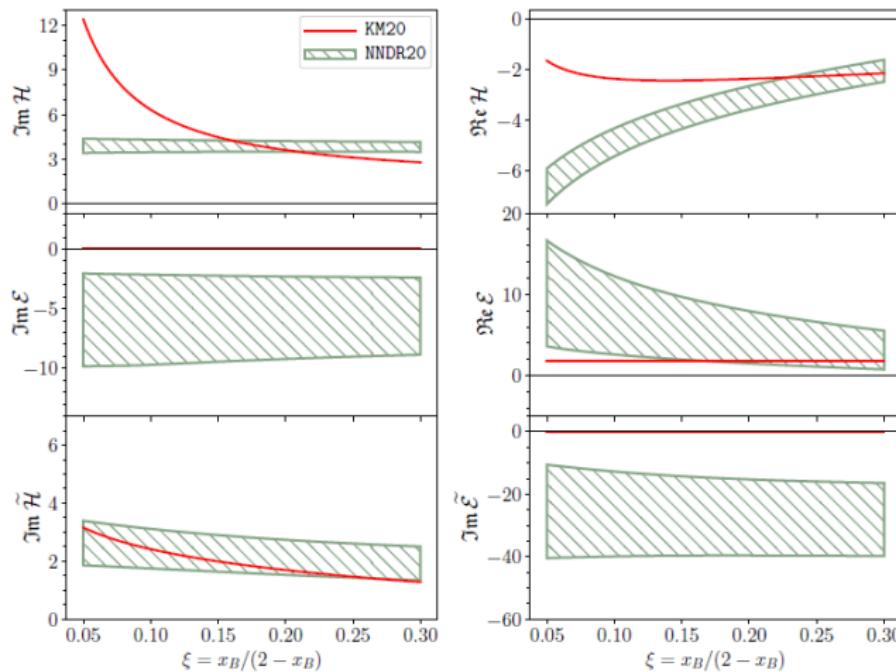
Results
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Results

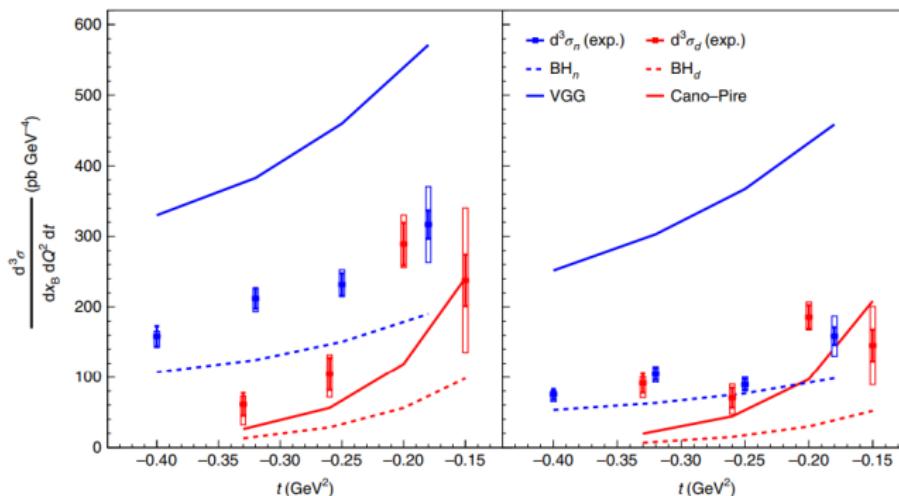
Extraction of 6 CFFs

[M. Čuić, K. Kumerički, A. Schäfer, '20], from JLab data



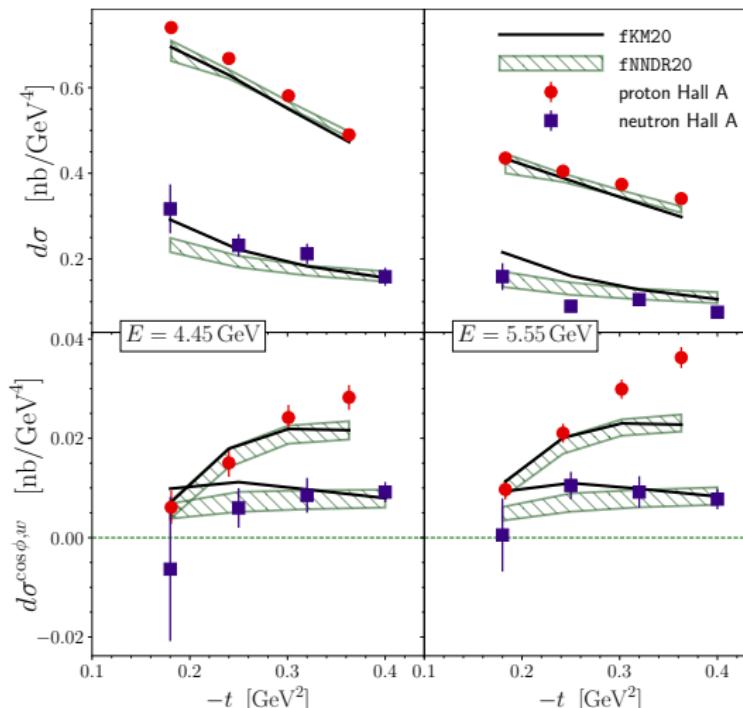
Neutron DVCS

[Benali et al. '20], DVCS off a deuterium target



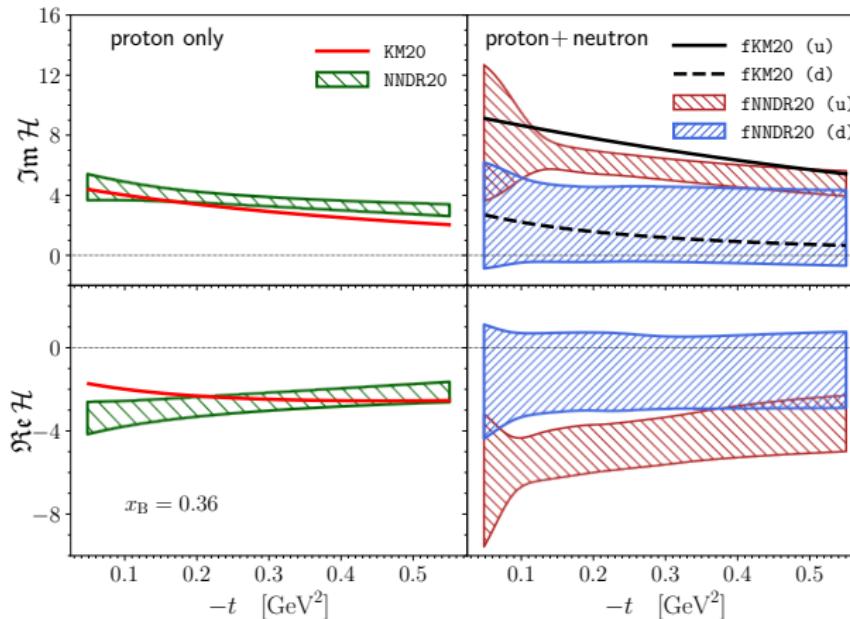
Using isospin symmetry (e.g. $H_{u,\text{proton}}^{\text{val}} = H_{d,\text{neutron}}^{\text{val}}$) we combine proton and neutron DVCS data to separate up and down quark contributions to CFFs.

- separate model for each flavor CFF: \mathcal{H}_u , \mathcal{H}_d
 - fKM20 "physical" flavored model, fNNDR neural nets and dispersion relations



Flavor CFFs

- up and down contributions to CFF \mathcal{H} cleanly separated

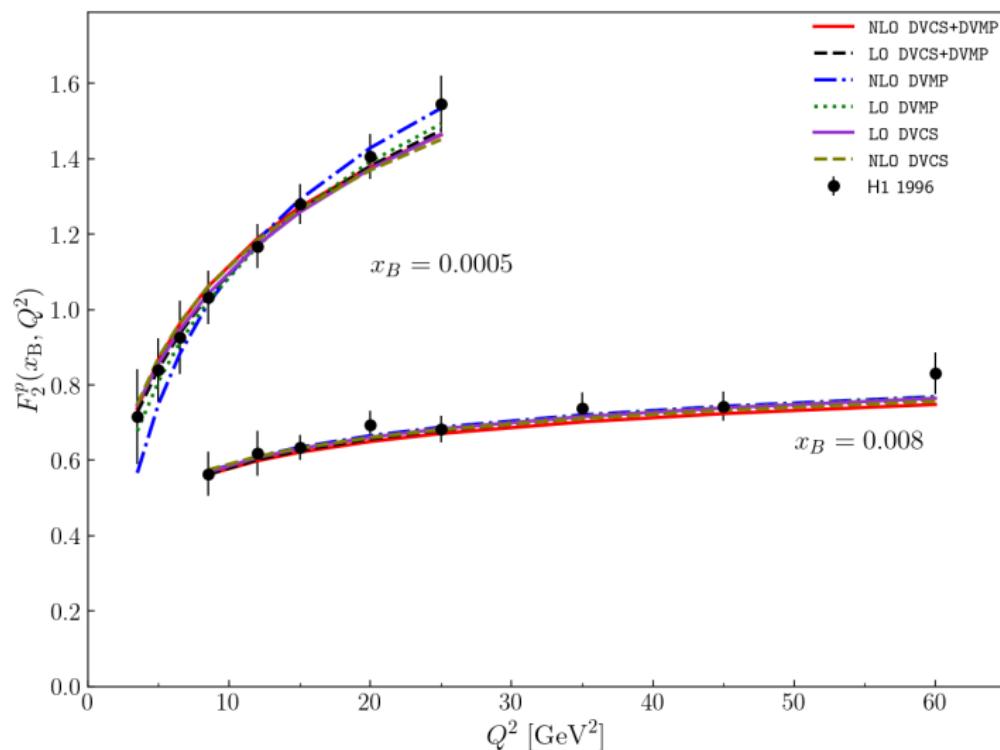


NLO DIS+DVCS+DVMP small- x global fit

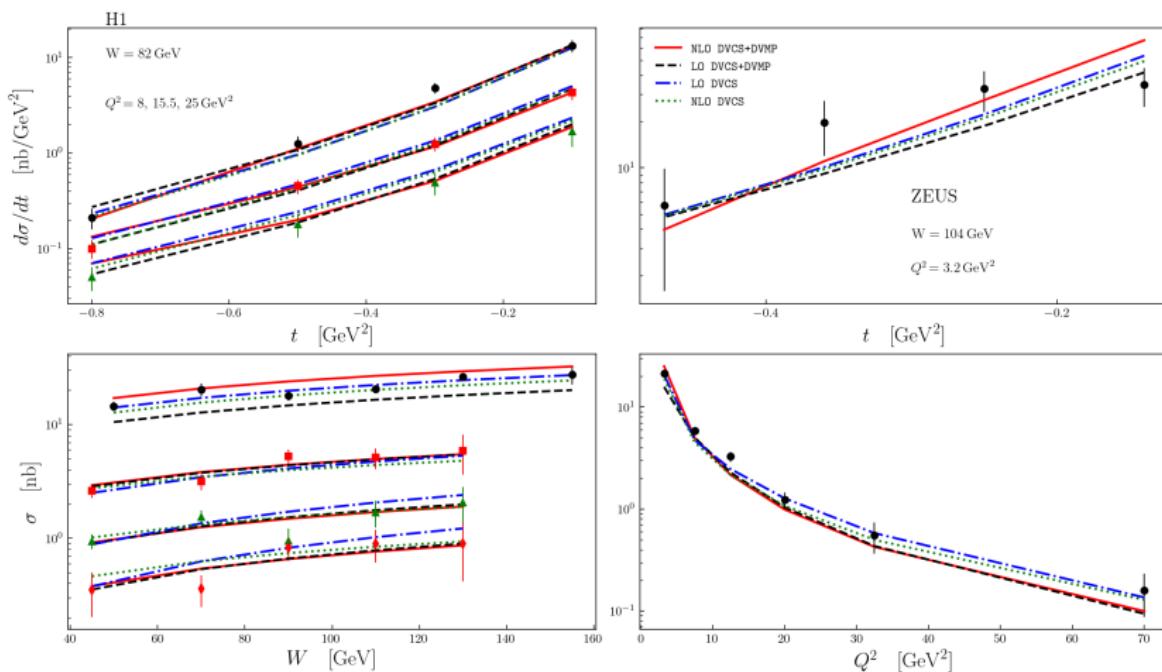
- First global fits to DIS+DVCS+DVMP HERA collider data
[Lautenschlager, Müller, Schäfer, '13, unpublished!]
- hard scattering amplitude corrected in the meantime
[Duplančić, Müller, Passek-Kumerički '17]

- [M. Čuić, K. Kumerički, '22] preliminary results for NLO DIS+DVCS+DVMP small- x global fit
- only considered sea quarks and gluons, full NLO Q^2 evolution
- ρ^0 and ϕ DVMP
- fit to HERA collider data (excluding t -dependent DVMP data): $\chi^2/n_{\text{d.o.f.}} = 205.41/203 \approx 1.01$
- 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?

DIS F_2 data description

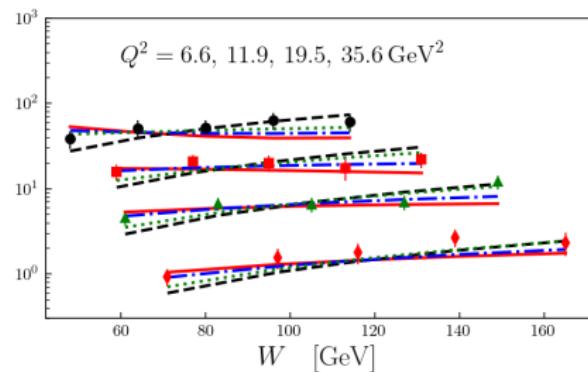
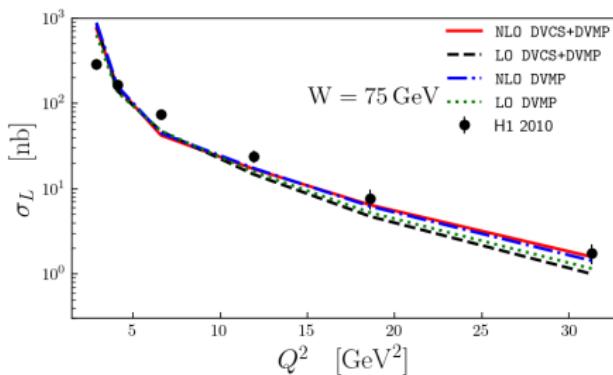


DVCS data description

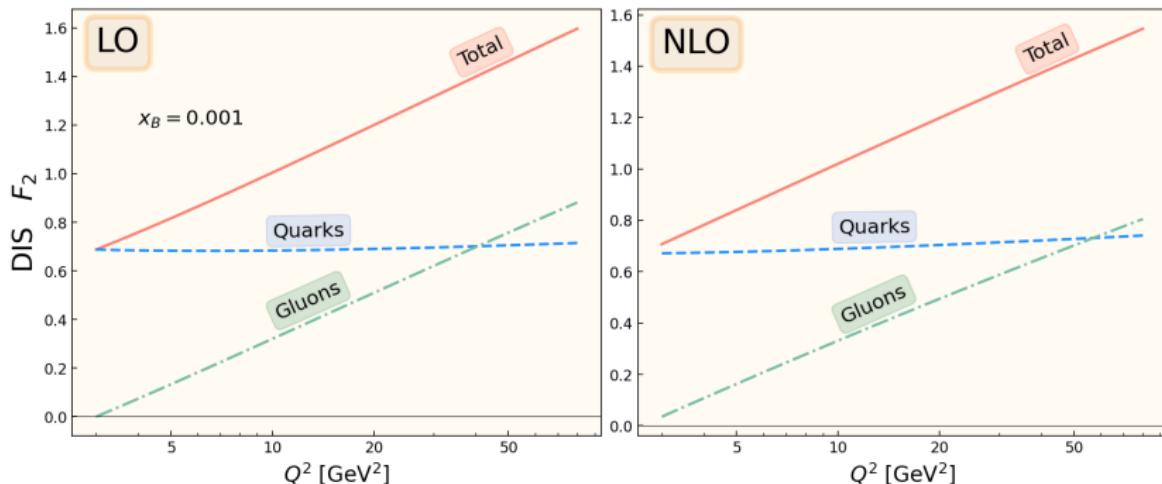


DVMP data description

H1 DVMP

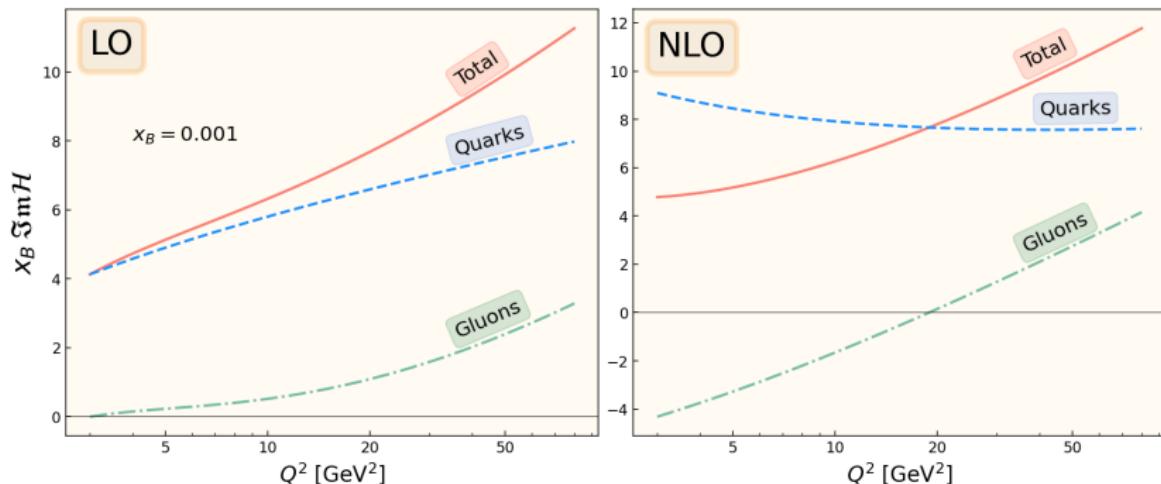


Quark and gluon contributions: DIS



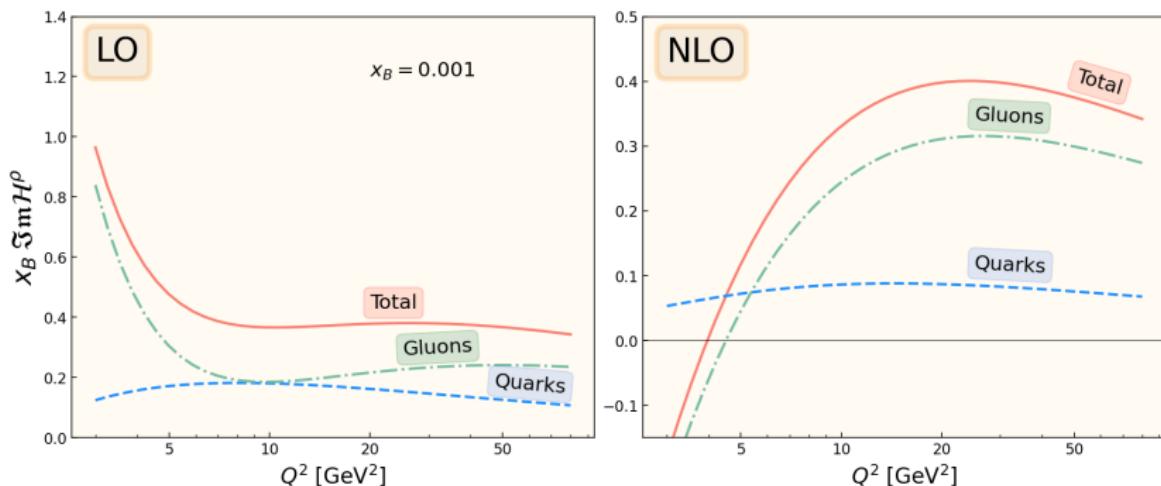
- at LO gluons do not contribute at low Q^2
- not much changes at NLO

Quark and gluon contributions: DVCS



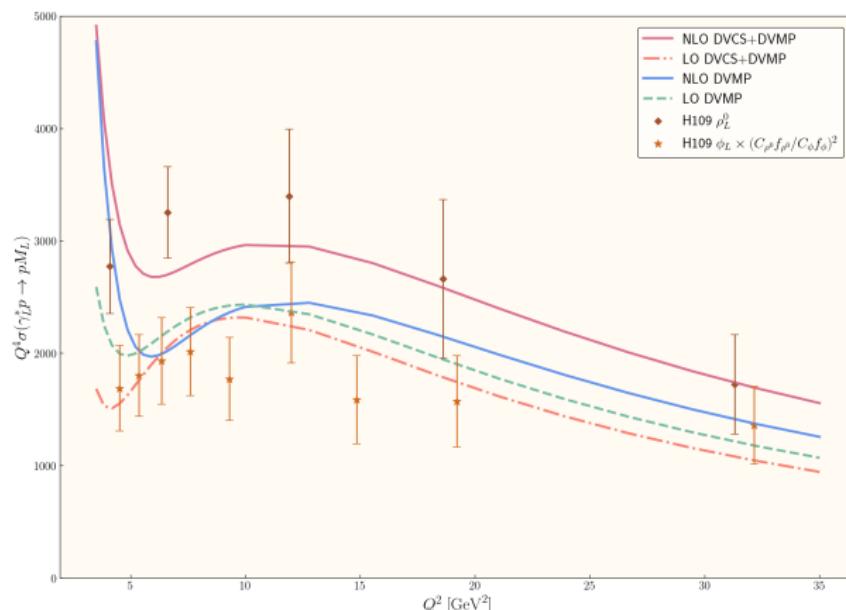
- at LO gluons do not contribute at low Q^2
- at NLO gluons negative at low Q^2

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 scaling

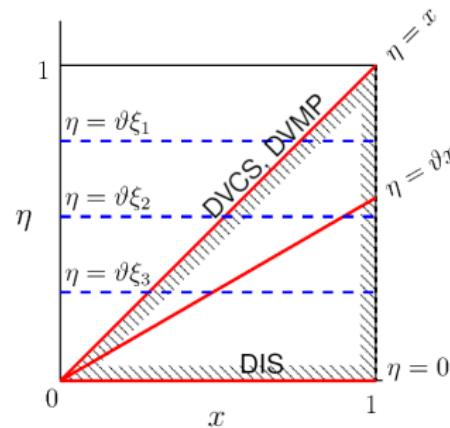


- theory scales roughly as Q^4 after ~ 10 GeV 2
- JLab@20+ opportunity

Skewness

- skewness: ratio of GPD to corresponding PDF

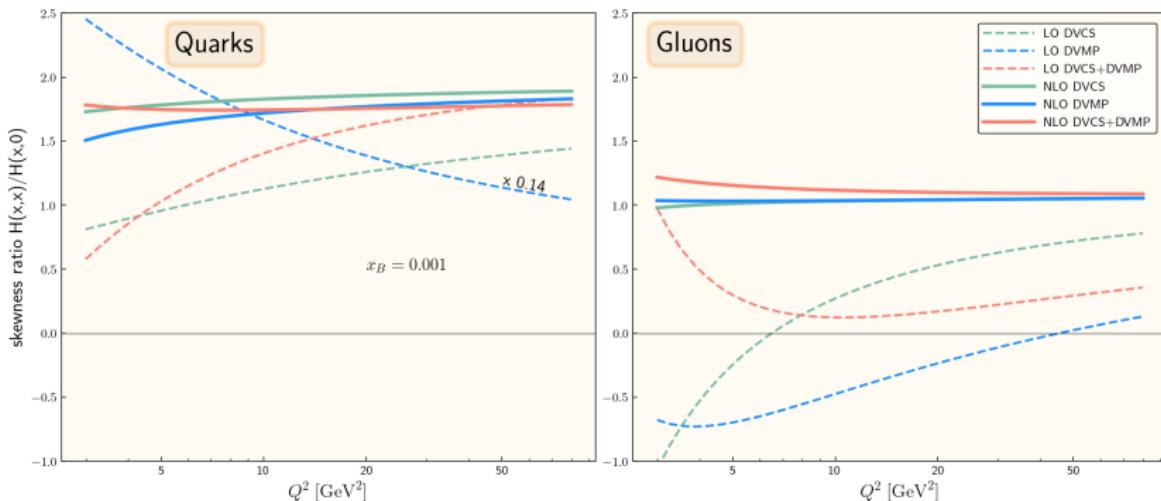
$$r = \frac{H(x, \eta = x)}{q(x)}$$



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

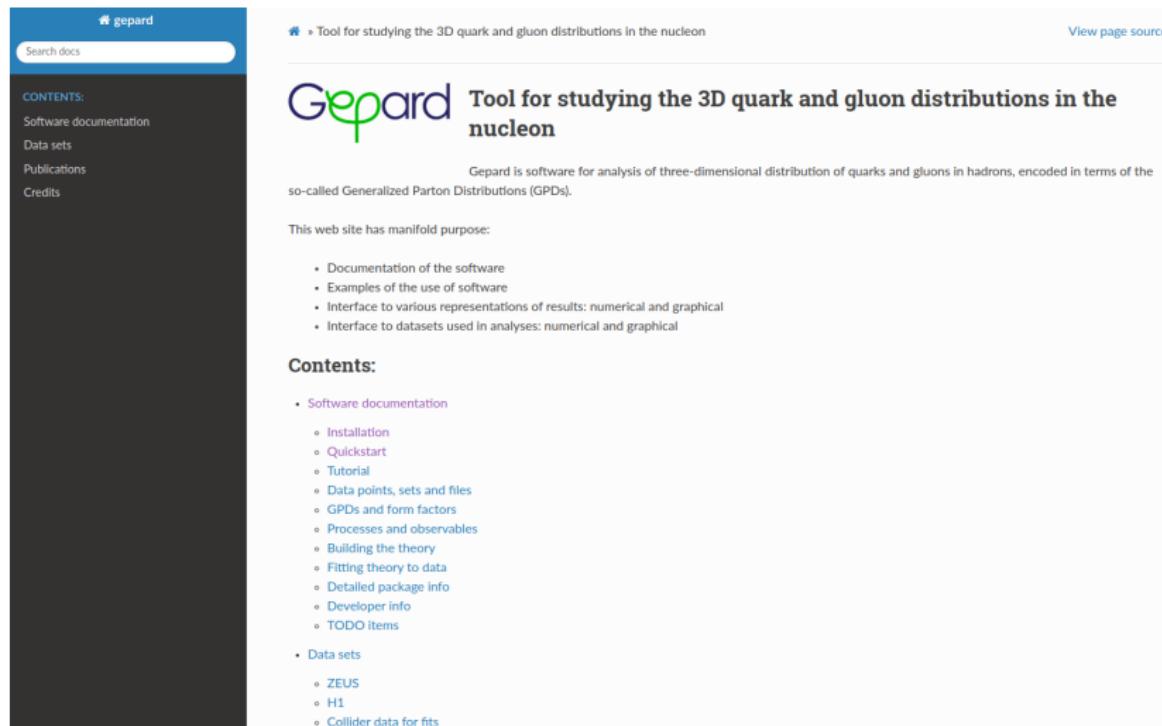
$$r^q \approx 1.65, \quad r^G \approx 1$$

Skewness at LO and NLO



Universal GPD structure emerges at NLO!

Open-source software Gepard <https://gepard.phy.hr>



The screenshot shows the homepage of the Gepard software. The header includes the logo "gepard" and a search bar. The main title is "Tool for studying the 3D quark and gluon distributions in the nucleon". Below the title, a brief description states: "Gepard is software for analysis of three-dimensional distribution of quarks and gluons in hadrons, encoded in terms of the so-called Generalized Parton Distributions (GPDs).". A note below says: "This web site has manifold purpose:". A bulleted list follows: Documentation of the software, Examples of the use of software, Interface to various representations of results: numerical and graphical, Interface to datasets used in analyses: numerical and graphical. A "Contents:" section lists: Software documentation (Installation, Quickstart, Tutorial, Data points, sets and files, GPDs and form factors, Processes and observables, Building the theory, Fitting theory to data, Detailed package info, Developer info, TODO items), and Data sets (ZEUS, H1, Collider data for fits).

gepard

Search docs

» Tool for studying the 3D quark and gluon distributions in the nucleon

View page source

Gepard Tool for studying the 3D quark and gluon distributions in the nucleon

Gepard is software for analysis of three-dimensional distribution of quarks and gluons in hadrons, encoded in terms of the so-called Generalized Parton Distributions (GPDs).

This web site has manifold purpose:

- Documentation of the software
- Examples of the use of software
- Interface to various representations of results: numerical and graphical
- Interface to datasets used in analyses: numerical and graphical

Contents:

- Software documentation
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 - TODO items
- Data sets
 - ZEUS
 - H1
 - Collider data for fits

Future plans

- improve model so that all parts are in j space
- implement pseudoscalar mesons
- study EIC kinematics