Probing GPDs in Ultraperipheral Collisions

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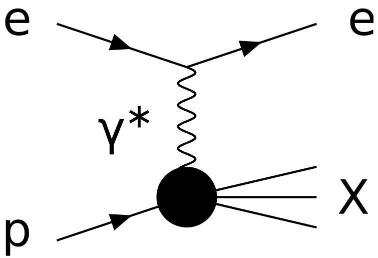
timelike-DVCS: B.Pire, L.Szymanowski
J/Ψ photoproduction: D.Ivanov, L.Szymanowski

Deep Inelastic Scattering $e\,p \to e\,X$



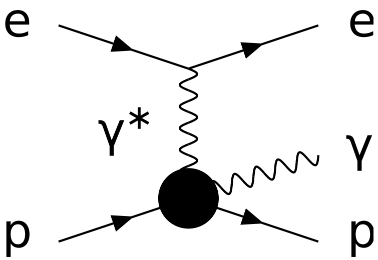
In the Björken limit i.e. when the photon virtality $Q^2 = -q^2$ and the squared hadronic c.m. energy $(p+q)^2$ become large, with the ratio $x_B = \frac{Q^2}{2p \cdot q}$ fixed, the cross section factorizes into a hard partonic subprocess calculable in the perturbation theory, and a parton distributions.

DIS

- Parton distributions encode the distribution of longitudinal momentum and polarization carried by quarks, antiquarks and gluons within fast moving hadron
- PDFs don't provide infomation about how partons are distributed in the transverse plane and ...
- about how important is the orbital angular momentum in making up the total spin of the nucleon.
- Recently - growing interest in the exclusive scattering processes, which may shed some light on these issues through the generalized parton distributions (GPDs) .

DVCS

The simplest and best known process is Deeply Virtual Compton Scattering: $e\,p \to e\,p\,\gamma$



Factorization into GPDs and perturbative coefficient function - on the level of amplitude.

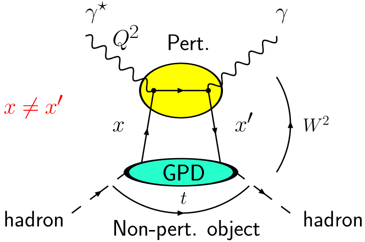
$$\text{DIS :} \qquad \sigma = \text{PDF} \otimes \text{partonic cross section}$$
$$\text{DVCS :} \qquad \mathcal{M} = \text{GPD} \otimes \text{partonic amplitude}$$

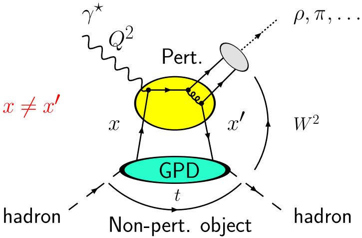
GPDs

- GPDs enter factorization theorems for hard exclusive reactions (DVCS, deeply virtual meson production, TCS etc.), in a similar manner as PDFs enter factorization theorems for inclusive (DIS, etc.)
- GPDs are functions of x, t, ξ, μ_F^2
- First moment of GPDs enters the Ji's sum rule for the angular momentum carried by partons in the nucleon,
- 2+1 imaging of nucleon,
- Deeply Virtual Compton Scattering (DVCS) is a golden channel for GPDs extraction,

DVCS - what else, and why

- Difficult: exclusivity, 3 variables, GPD enter through convolutions, only GPD(ξ, ξ, t) accesible through DVCS at LO!
- universality,
- flavour separation,





- Meson production - additional information (and difficulties),

So, in addition to spacelike DVCS ...

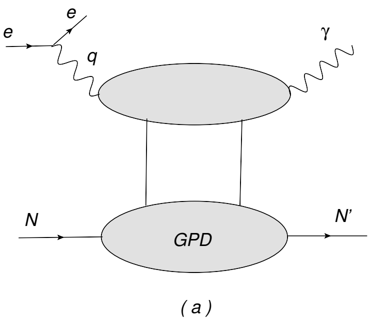


Figure: Deeply Virtual Compton Scattering (DVCS) : $lN \to l'N'\gamma$

we can also study timelike DVCS

Berger, Diehl, Pire, 2002

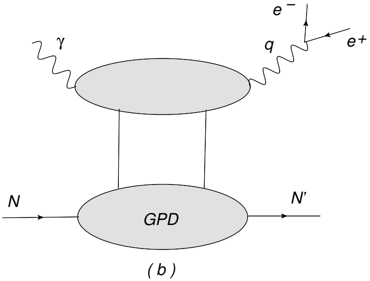


Figure: Timelike Compton Scattering (TCS): $\gamma N \to l^+ l^- N'$

Why TCS:

- universality of the GPDs
- another source for GPDs (special sensitivity on real part of GPD H),
- spacelike-timelike crossing,
- first step towards DDCVS,

General Compton Scattering:

$$\gamma^*(q_{in})N(p) \to \gamma^*(q_{out})N'(p')$$

variables, describing the processes of interest in this generalized Bjorken limit, are the scaling variable ξ and skewness $\eta > 0$:

$$\xi = -\frac{q_{out}^2 + q_{in}^2}{q_{out}^2 - q_{in}^2}\eta\,, \quad \eta = \frac{q_{out}^2 - q_{in}^2}{(p+p')\cdot(q_{in}+q_{out})}\,.$$

- DDVCS: $q_{in}^2 < 0\,, \quad q_{out}^2 > 0\,, \quad \eta \neq \xi$
- DVCS: $q_{in}^2 < 0\,, \quad q_{out}^2 = 0\,, \quad \eta = \xi > 0$
- TCS: $q_{in}^2 = 0\,, \quad q_{out}^2 > 0\,, \quad \eta = -\xi > 0$

Coefficient functions and Compton Form Factors

CFFs are the GPD dependent quantities which enter the amplitudes. They are defined through relations:

$$\mathcal{A}^{\mu\nu}(\xi,\eta,t) = -e^2 \frac{1}{(P+P')^+}\,\bar{u}(P')\left[g_T^{\mu\nu}\left(\mathcal{H}(\xi,\eta,t)\,\gamma^+ + \mathcal{E}(\xi,\eta,t)\,\frac{i\sigma^{+\rho}\Delta_\rho}{2M}\right)\right.$$
$$\left. + i\epsilon_T^{\mu\nu}\left(\widetilde{\mathcal{H}}(\xi,\eta,t)\,\gamma^+\gamma_5 + \widetilde{\mathcal{E}}(\xi,\eta,t)\,\frac{\Delta^+\gamma_5}{2M}\right)\right] u(P)\,,$$

,where:

$$\begin{aligned}
\mathcal{H}(\xi,\eta,t) &= +\int_{-1}^{1} dx\left(\sum_q T^q(x,\xi,\eta)H^q(x,\eta,t) + T^g(x,\xi,\eta)H^g(x,\eta,t)\right)\\
\widetilde{\mathcal{H}}(\xi,\eta,t) &= -\int_{-1}^{1} dx\left(\sum_q \widetilde{T}^q(x,\xi,\eta)\widetilde{H}^q(x,\eta,t) + \widetilde{T}^g(x,\xi,\eta)\widetilde{H}^g(x,\eta,t)\right).
\end{aligned}$$

LO and NLO Coefficient functions

- DVCS vs TCS at LO

$$
\begin{aligned}
{}^{DVCS}T^q &= -e_q^2 \tfrac{1}{x+\eta-i\varepsilon} - (x \to -x) = & ({}^{TCS}T^q)^* \\
{}^{DVCS}\tilde{T}^q &= -e_q^2 \tfrac{1}{x+\eta-i\varepsilon} + (x \to -x) = & -({}^{TCS}\tilde{T}^q)^*
\end{aligned}
$$

$$
{}^{DVCS}Re(\mathcal{H}) \sim P\int \frac{1}{x \pm \eta} H^q(x,\eta,t)\,, \qquad {}^{DVCS}Im(\mathcal{H}) \sim i\pi H^q(\pm\eta,\eta,t)
$$

- DDVCS at LO

$$
{}^{DDVCS}T^q = -e_q^2 \frac{1}{x+\xi-i\varepsilon} - (x \to -x)
$$

$$
{}^{DDVCS}Re(\mathcal{H}) \sim P\int \frac{1}{x \pm \xi} H^q(x,\eta,t)\,, \qquad {}^{DVCS}Im(\mathcal{H}) \sim i\pi H^q(\pm\xi,\eta,t)
$$

But this is only true at LO. At NLO all GPDs hidden in the convolutions.

- DVCS vs TCS at LO

The results for DVCS and TCS cases are simply related:

$$
{}^{TCS}T(x,\eta) = \pm\left({}^{DVCS}T(x,\xi=\eta) + i\pi \cdot C_{coll}(x,\xi=\eta)\right)^* \;,
$$

D.Mueller, B.Pire, L.Szymanowski, J.Wagner, Phys.Rev.D86.

Moutarde, Pire, Sabatié, Szymanowski, Wagner , Phys.Rev.D87.

TCS and Bethe-Heitler contribution to exclusive lepton pair photoproduction.

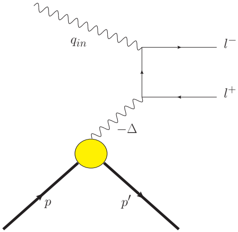


Figure: The Feynman diagram for the Bethe-Heitler amplitude.

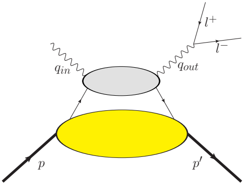


Figure: The Feynman diagram for the Compton amplitude.

TCS

Berger, Diehl, Pire, 2002

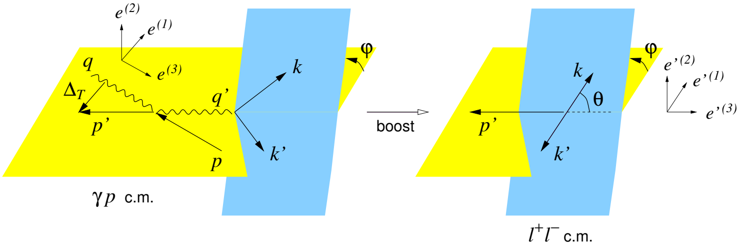


Figure: Kinematical variables and coordinate axes in the γp and $\ell^+\ell^-$ c.m. frames.

Interference

B-H dominant for not very high energies:

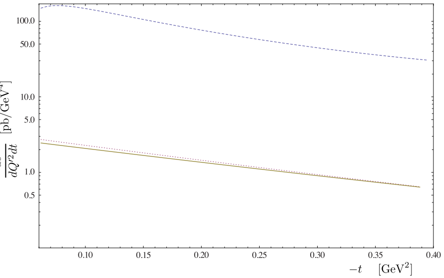


Figure: LO (dotted) and NLO (solid) TCS and Bethe-Heitler (dash-dotted) contributions to the cross section as a function of t for $Q^2 = \mu^2 = 4\,\mathrm{GeV}^2$ integrated over $\theta \in (\pi/4; 3\pi/4)$ and over $\phi \in (0; 2\pi)$ for $E_\gamma = 10\,\mathrm{GeV}(\eta \approx 0.11)$.

The interference part of the cross-section for $\gamma p \to \ell^+ \ell^- \, p$ with unpolarized protons and photons is given by:

$$\frac{d\sigma_{INT}}{dQ'^2\, dt\, d\cos\theta\, d\varphi} \sim \cos\varphi \cdot \ \mathrm{Re}\,\mathcal{H}(\eta, t)$$

Linear in GPD's, odd under exchange of the l^+ and l^- momenta $\Rightarrow$ angular distribution of lepton pairs is a good tool to study interference term.

JLAB 6 GeV data

Rafayel Paremuzyan PhD thesis

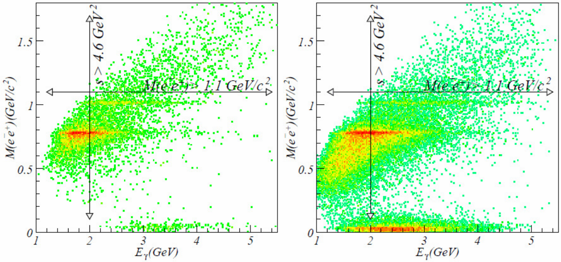


Figure: e^+e^- invariant mass distribution vs quasi-real photon energy. For TCS analysis $M(e^+e^-) > 1.1\,\mathrm{GeV}$ and $s_{\gamma p} > 4.6\,\mathrm{GeV}^2$ regions are chosen. Left graph represents e1-6 data set, right one is from e1f data set.

Theory vs experiment

R.Paremuzyan and V.Guzey:

$$R = \frac{\int d\phi \ \cos\phi \int d\theta \ d\sigma}{\int \ d\phi \int d\theta \ d\sigma}$$

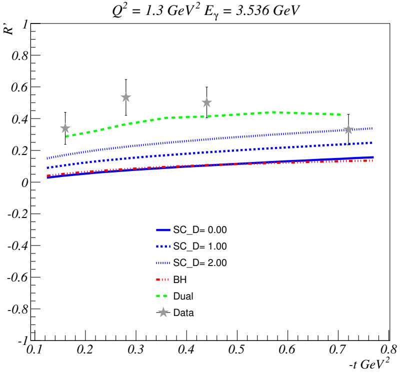


Figure: Thoeretical prediction of the ratio R for various GPDs models. Data points after combining both e1-6 and e1f data sets.

Jefferson Lab PAC 39 Proposal
Timelike Compton Scattering and J/ψ photoproduction on the proton in e^+e^- pair production with CLAS12 at 11 GeV

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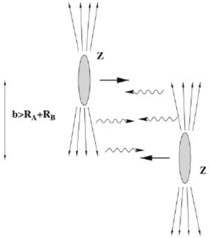
Approved experiment at Hall B, and LOI for Hall A.

Ultraperipheral collisions



$$\sigma^{AB} = \int dk_A \frac{dn^A}{dk_A} \sigma^{\gamma B}(W_A(k_A)) + \int dk_B \frac{dn^B}{dk_B} \sigma^{\gamma A}(W_B(k_B))$$

where $k_{A,B} = \frac{1}{2} x_{A,B} \sqrt{s}$.

BH cross section at UPC

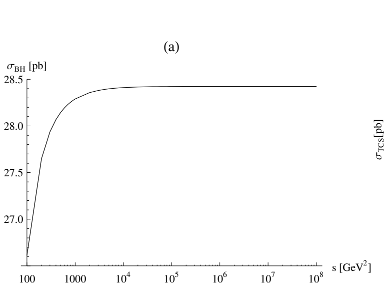


Figure: (a) The BH cross section integrated over $\theta \in [\pi/4, 3\pi/4]$, $\varphi \in [0, 2\pi]$, $Q'^2 \in [4.5, 5.5]\,\mathrm{GeV}^2$, $|t| \in [0.05, 0.25]\,\mathrm{GeV}^2$, as a function of γp c.m. energy squared s. (b) σ_{TCS} as a function of γp c.m. energy squared s, for GRVGJR2008 NLO parametrizations, for different factorization scales $\mu_F^2 = 4$ (dotted), 5 (dashed), 6 (solid) GeV^2.

For very high energies σ_{TCS} calculated with $\mu_F^2 = 6\,\mathrm{GeV}^2$ is much bigger then with $\mu_F^2 = 4\,\mathrm{GeV}^2$. Also predictions obtained using LO and NLO GRVGJR2008 PDFs differ significantly.

The interference cross section at UPC

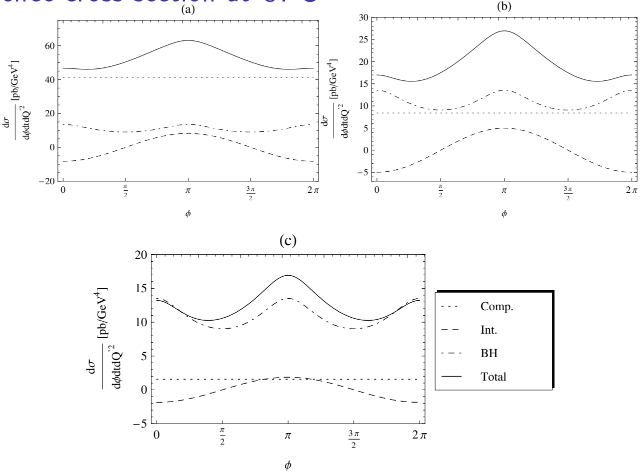


Figure: The differential cross sections (solid lines) for $t = -0.2\,\mathrm{GeV}^2$, $Q'^2 = 5\,\mathrm{GeV}^2$ and integrated over $\theta = [\pi/4, 3\pi/4]$, as a function of φ, for $s = 10^7\,\mathrm{GeV}^2$ (a), $s = 10^5\,\mathrm{GeV}^2$(b), $s = 10^3\,\mathrm{GeV}^2$ (c) with $\mu_F^2 = 5\,\mathrm{GeV}^2$. We also display the Compton (dotted), Bethe-Heitler (dash-dotted) and Interference (dashed) contributions.

UPC Rate estimates

The pure Bethe - Heitler contribution to σ_{pp}, integrated over $\theta = [\pi/4, 3\pi/4]$, $\phi = [0, 2\pi]$, $t = [-0.05\,\mathrm{GeV}^2, -0.25\,\mathrm{GeV}^2]$, $Q'^2 = [4.5\,\mathrm{GeV}^2, 5.5\,\mathrm{GeV}^2]$, and photon energies $k = [20, 900]\,\mathrm{GeV}$ gives:

$$\sigma_{pp}^{BH} = 2.9\text{pb} \; .$$

The Compton contribution (calculated with NLO GRVGJR2008 PDFs, and $\mu_F^2 = 5\,\mathrm{GeV}^2$) gives:

$$\sigma_{pp}^{TCS} = 1.9\text{pb} \; .$$

LHC: rate $\sim 10^5$ events/year with nominal luminosity (10^{34} cm^{-2}s^{-1})

Gluon GPDs in the UPC production of heavy mesons

Work in progress with D.Yu.Ivanov and L.Szymanowski

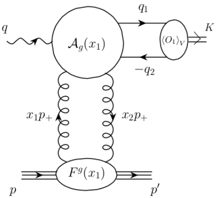


Figure 1: Kinematics of heavy vector meson photoproduction.

D. Yu. Ivanov , A. Schafer , L. Szymanowski and G. Krasnikov - **Eur.Phys.J. C34 (2004) 297-316**

The amplitude $\mathcal{M}$ is given by factorization formula:

$$\mathcal{M} \sim \left(\frac{\langle O_1 \rangle_V}{m^3} \right)^{1/2} \int_{-1}^{1} dx \left[T_g(x,\xi)\, F^g(x,\xi,t) + T_q(x,\xi) F^{q,S}(x,\xi,t) \right] ,$$

$$F^{q,S}(x,\xi,t) = \sum_{q=u,d,s} F^q(x,\xi,t) .$$

where m is a pole mass of heavy quark, $\langle O_1 \rangle_V$ is given by NRQCD through leptonic meson decay rate.

Hard scattering kernels

$$T_g(x,\xi) = \frac{\xi}{(x-\xi+i\varepsilon)(x+\xi-i\varepsilon)}\mathcal{A}_g\left(\frac{x-\xi+i\varepsilon}{2\xi}\right),$$
$$T_q(x,\xi) = \mathcal{A}_q\left(\frac{x-\xi+i\varepsilon}{2\xi}\right).$$

- LO

$$\mathcal{A}_g^{(0)}(y) = \alpha_S\,, \qquad \text{In the first paper it was :} \quad \alpha_S(1+\epsilon)$$
$$\mathcal{A}_q^{(0)}(y) = 0\,.$$

- NLO

  $T_g(x,\xi)$ - unchanged, and in $T_q(x,\xi)$ one has to correct:

$$\left(\log\frac{4m^2}{\mu_F^2} - 1\right) \to \left(\log\frac{4m^2}{\mu_F^2}\right)$$

  Erratum is being written, but phenomenological consequences unchanged.

Photoproduction amplitude and cross section - LO

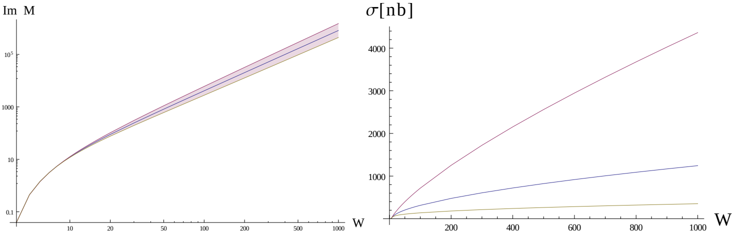


Figure: (left) Imaginary part of the amplitude $\mathcal{M}$ and (right) photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$.

Photoproduction amplitude and cross section - LO and NLO.

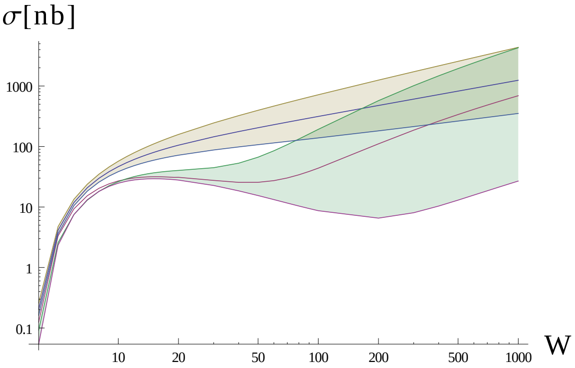


Figure: Photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$- LO and NLO

Photoproduction cross section

NLO/LO for large W:

$$\sim \frac{\alpha_S(\mu_R) N_c}{\pi} \ln\left(\frac{1}{\xi}\right) \ln\left(\frac{\frac{1}{4}M_V^2}{\mu_F^2}\right)$$

What to do ??? (PMS??, BLM??, resummation?,...?)

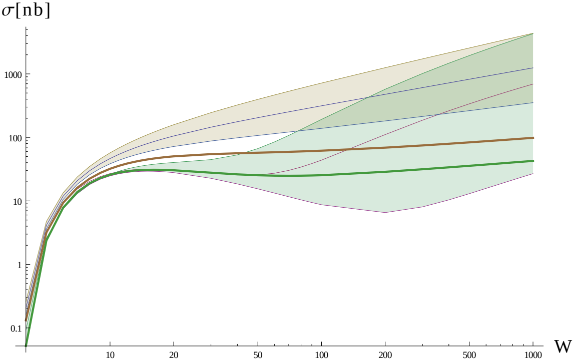
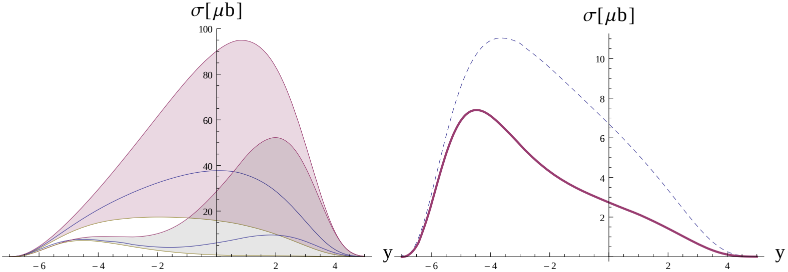


Figure: Photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$- LO and NLO. Thick lines for LO and NLO for $\mu_F^2 = 1/4 M_{J/\psi}^2$.

UPC cross section

Cross section for Ultraperipheral p-Pb collision in the EPA, $\sqrt{s} = 5\ \mathrm{TeV}$ as a function of y.



(left) LO and NLO $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$.
(right) LO and NLO for $\mu_F^2 = 1/4 M_{J/\psi}^2$.

Summary

- GDPs enter factorization theorems for hard exclusive reactions (DVCS, deeply virtual meson production etc.), in a similar manner as PDFs enter factorization theorem for DIS - Ji's sum rule, „tomographic" 3D images
- DVCS is a golden channel, a lot of new experiments planned to measure DVCS - JLAB 12, COMPASS, EIC(?)
- ,but we want to descibe other exclusve processes - TCS, double DVCS, DVMP, photoproduction of heavy mesons...
- TCS already measured at JLAB 6 GeV, but much richer and more interesting kinematical region available after upgrade to 12 GeV, maybe possible at COMPASS.
- Ultraperipheral collisions at hadron colliders opens a new way to measure GPDs,
- NLO corrections very important, also important for GPD extraction at $\xi \neq x$.
- Situation for Υ should be better - higher factorization scale, and ξ not that small (comparing to J/Ψ).