Probing GPDs in photoproduction processes at hadron colliders

Dmitry Ivanov

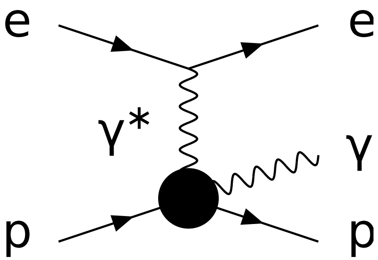
Sobolev Institute of Mathematics

PHOTON 2015, Novosibirsk

timelike-DVCS (review of work): B. Pire, L. Szymanowski, J. Wagner
J/Ψ photoproduction (in progress): D. Ivanov, L.Szymanowski, J. Wagner

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.

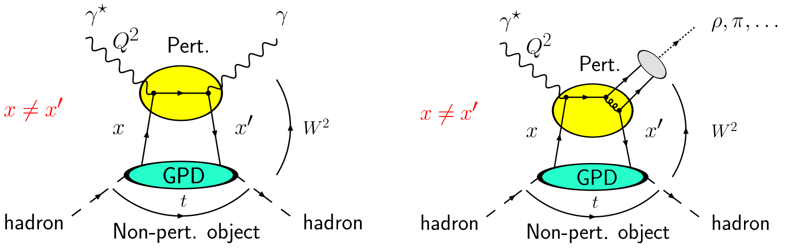
$$\begin{aligned} \text{DIS :} \qquad & \sigma = \text{PDF} \otimes \text{partonic cross section} \\ \text{DVCS :} \qquad & \mathcal{M} = \text{GPD} \otimes \text{partonic amplitude} \end{aligned}$$

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, DVMP

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



$$x' = x - \xi \;, \quad \xi \sim \frac{Q^2}{W^2}$$

So, in addition to spacelike DVCS ...

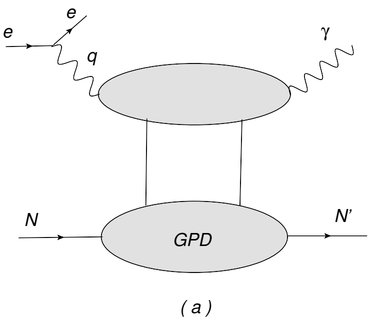


Figure: Deeply Virtual Compton Scattering (DVCS) : $lN \to l'N'\gamma$

we can also study timelike DVCS

Berger, Diehl, Pire, 2002

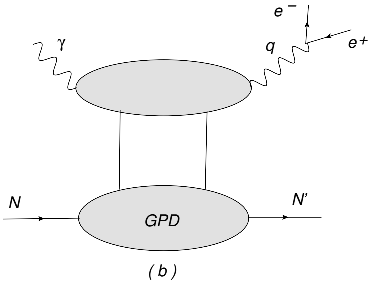


Figure: Timelike Compton Scattering (TCS): $\gamma N \to l^+ l^- N'$

Why TCS:

- universality of the GPDs
- another source for GPDs
- spacelike-timelike crossing
- could be studied both in ep and pp

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

Coefficient functions and Compton Form Factors

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

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

FACTORIZATION:

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

LO and NLO Coefficient functions

- DVCS vs TCS at LO are simply related:

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

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

- 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.

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

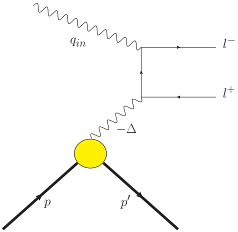


Figure: The Feynman diagram for the Bethe-Heitler amplitude.

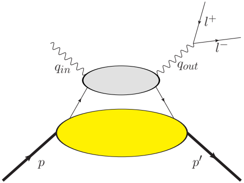


Figure: The Feynman diagram for the Compton amplitude.

TCS

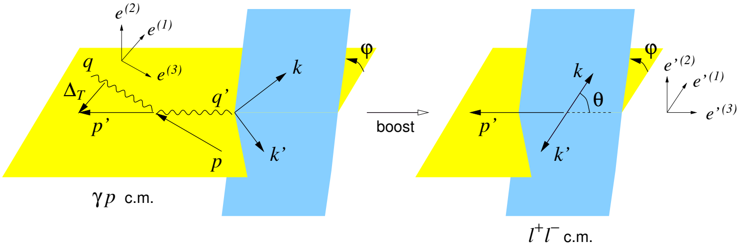


Figure: Kinematical variables and coordinate axes in the γp and $\ell^+\ell^-$ c.m. frames.

B-H dominant for not very high energies. Therefore we need the interference part of the cross-section. For unpolarized protons and photons:

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

JLAB 6 GeV data

Rafayel Paremuzyan PhD thesis

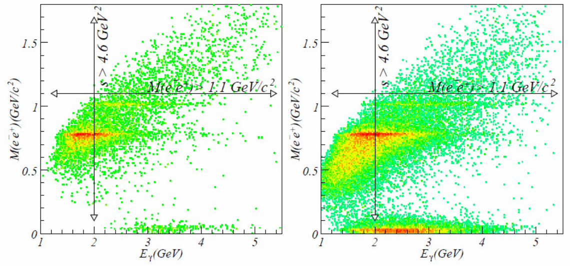


Figure: e^+e^- invariant mass distribution vs quasi-real photon energy. For TCS analysis $M(e^+e^-) > 1.1\,\mathrm{GeV}$ and $s_{\gamma p} > 4.6\,\mathrm{GeV}^2$ regions are chosen. Left graph represents e1-6 data set, right one is from e1f data set.

Theory vs experiment

R.Paremuzyan and V.Guzey:

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

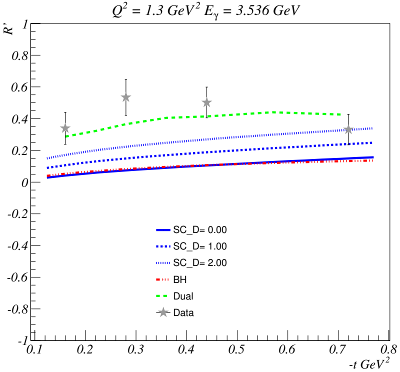


Figure: Thoeretical prediction of the ratio R for various GPDs models. Data points after combining both e1-6 and e1f data sets.

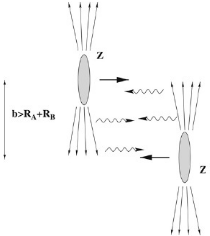
Jefferson Lab PAC 39 Proposal
Timelike Compton Scattering and J/ψ photoproduction on the proton in e^+e^- pair production with CLAS12 at 11 GeV

I. Albayrak,[1] V. Burkert,[2] E. Chudakov,[2] N. Dashyan,[3] C. Desnault,[4] N. Gevorgyan,[3] Y. Ghandilyan,[3] B. Guegan,[4] M. Guidal*,[4] V. Guzey,[2,5] K. Hicks,[6] T. Horn*,[1] C. Hyde,[7] Y. Ilieva,[8] H. Jo,[4] P. Khetarpal,[9] F.J. Klein,[1] V. Kubarovsky,[2] A. Marti,[4] C. Munoz Camacho,[4] P. Nadel-Turonski*†,[2] S. Niccolai,[4] R. Paremuzyan*,[4,3] B. Pire,[10] F. Sabatié,[11] C. Salgado,[12] P. Schweitzer,[13] A. Simonyan,[3] D. Sokhan,[4] S. Stepanyan*,[2] L. Szymanowski,[14] H. Voskanyan,[3] J. Wagner,[14] C. Weiss,[2] N. Zachariou,[8] and the CLAS Collaboration.

[1]*Catholic University of America, Washington, D.C. 20064*
[2]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606*
[3]*Yerevan Physics Institute, 375036 Yerevan, Armenia*
[4]*Institut de Physique Nucleaire d'Orsay, IN2P3, BP 1, 91406 Orsay, France*
[5]*Hampton University, Hampton, Virginia 23668*
[6]*Ohio University, Athens, Ohio 45701*

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 and TCS cross sections at UPC

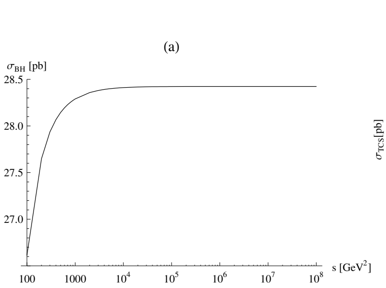


Figure: (a) The BH cross section integrated over $\theta \in [\pi/4, 3\pi/4]$, $\varphi \in [0, 2\pi]$, $Q'^2 \in [4.5, 5.5]\,\mathrm{GeV}^2$, $|t| \in [0.05, 0.25]\,\mathrm{GeV}^2$, as a function of γp c.m. energy squared s. (b) σ_{TCS} as a function of γp c.m. energy squared s, for GRVGJR2008 NLO parametrizations,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

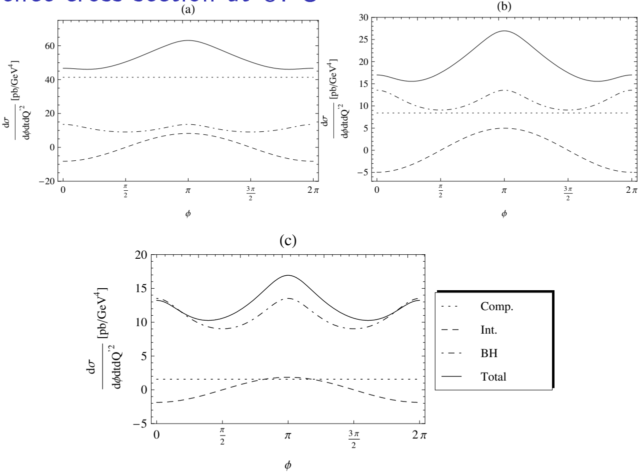


Figure: The differential cross sections (solid lines) for $t = -0.2\,\mathrm{GeV}^2$, $Q'^2 = 5\,\mathrm{GeV}^2$ and integrated over $\theta = [\pi/4, 3\pi/4]$, as a function of φ, for $s = 10^7\,\mathrm{GeV}^2$ (a), $s = 10^5\,\mathrm{GeV}^2$(b), $s = 10^3\,\mathrm{GeV}^2$ (c) with $\mu_F^2 = 5\,\mathrm{GeV}^2$.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

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

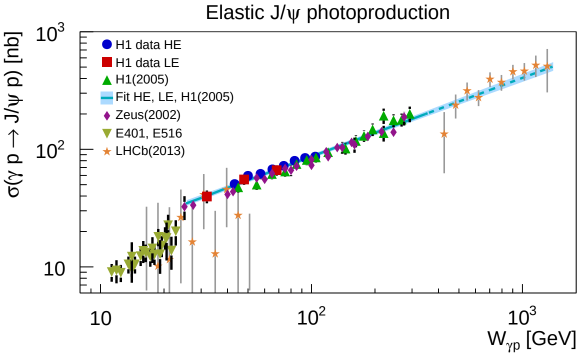
The Compton contribution (calculated with NLO GRVGJR2008 PDFs, and $\mu_F^2 = 5\,\mathrm{GeV}^2$) gives:

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

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

Could one access GPDs in the UPC production of heavy mesons?

We have good data! See H1 2013 paper:



Combined Collinear QCD and NRQCD factorizations:

twist $\sim 1/M^n$ and velocity $\sim \left(\frac{v}{c}\right)^m$ expansions:

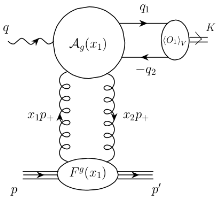


Figure 1: Kinematics of heavy vector meson photoproduction.

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

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

$F^{g(q)}(x,\xi,t;\mu_F^2)$ – the gluon (quark) GPDs, m is a pole mass of heavy quark, $\xi = M^2/(2W^2 - M^2)$ is the skewedness paramerer.
NRQCD – all information about the quarkonium structure is encoded in the NRQCD matrix element $\langle O_1\rangle_V$ which enters the leptonic decay rate

$$\Gamma[V \to l^+l^-] = \frac{2e_q^2\pi\alpha^2}{3}\,\frac{\langle O_1\rangle_V}{m^2}\left(1 - \frac{8\alpha_S}{3\pi}\right)^2 .$$

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

$$\mathcal{A}_g^{(0)}(y) = \alpha_S \quad \mathcal{A}_q^{(0)}(y) = 0\,.$$

- NLO

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

$$T_q(x,\xi) = \frac{\alpha_S^2(\mu_R)C_F}{2\pi} f_q\left(\frac{x-\xi+i\varepsilon}{2\xi}\right),$$

$$\begin{aligned} f_q(y) = {} & \ln\left(\frac{4m^2}{\mu_F^2}\right)(1+2y)\left(\frac{\ln(-y)}{1+y} - \frac{\ln(1+y)}{y}\right) - \pi^2\frac{13(1+2y)}{48y(1+y)} + \frac{2\ln 2}{1+2y} \\ & + \frac{\ln(-y)+\ln(1+y)}{1+2y} + (1+2y)\left(\frac{\ln^2(-y)}{1+y} - \frac{\ln^2(1+y)}{y}\right) \\ & + \frac{3-4y+16y(1+y)}{4y(1+y)}Li_2(1+2y) - \frac{7+4y+16y(1+y)}{4y(1+y)}Li_2(-1-2y) \end{aligned}$$

Photoproduction amplitude and cross section - LO

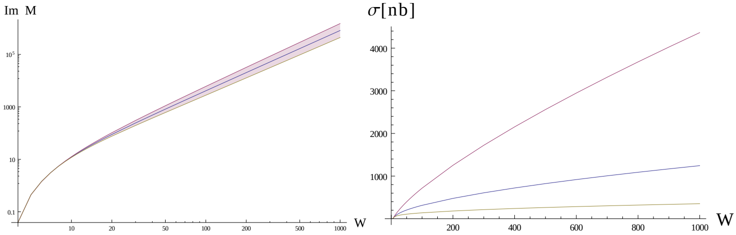


Figure: (left) Imaginary part of the amplitude $\mathcal{M}$ and (right) photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$.

Photoproduction cross section - LO and NLO

NLO/LO for large W:

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

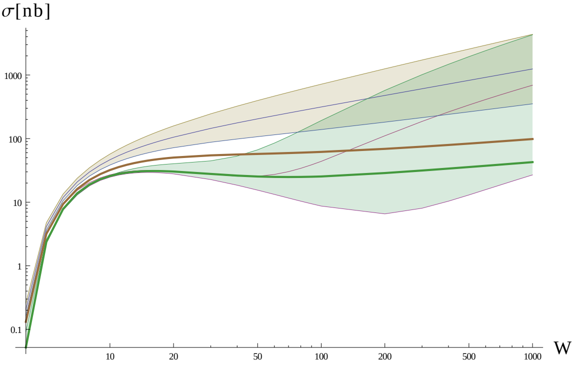


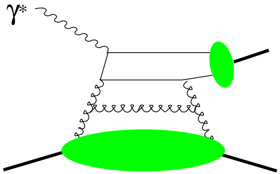
Figure: Photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$- LO and NLO. Thick lines for LO and NLO for $\mu_F^2 = 1/4 M_{J/\psi}^2$.

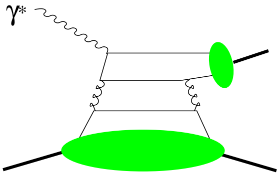
High-energy resummation

- Why NLO corrections are large at small x_B?
  large contribution comes from $\xi \ll x \ll 1$ ($Q = M$)

$$ImA^g \sim H^g(\xi,\xi) + \frac{3\alpha_s}{\pi}\left[\log\frac{Q^2}{\mu_F^2} - \log 4\right]\int\limits_{\xi}^{1}\frac{dx}{x}H^g(x,\xi)$$

$H^g(x,\xi) \sim xg(x) \sim const$, therefore $\int dx/xH^g(x,\xi) \sim \log(1/\xi)H^g(\xi,\xi)$
$x \sim \frac{s_{\gamma^* g}}{Q^2}$, Born contribution for BFKL:





At higher orders powers of energy log are generated

$$\mathcal{I}m A^g \sim H^g(\xi,\xi) + \int\limits_{\xi}^{1} \frac{dx}{x} H^g(x,\xi) \sum_{n=1} C_n(L) \frac{\bar{\alpha}_s^n}{(n-1)!} \log^{n-1}\frac{x}{\xi}$$

$C_n(L)$ - polynomials of $L = \log\frac{Q^2}{\mu_F^2}$, maximum power is L^n

- One can calculate $C_n(L)$ using BFKL equation in $D = 4 + 2\epsilon$ dimensions.
- Consistently with collinear factorization, in terms of corrections to coeff. functions and anomalous dimensions; say, in $\overline{MS}$ scheme
- for DIS a technique suggested by Catani, Ciafaloni and Hautmann; [Catani, Hautmann '94]
- The method used in DIS can be generalized to exclusive, nonforward processes.

Coeff. functions at small x / their Mellin moments at $N \to 0$

$$L = \log\left(\frac{Q^2}{\mu_F^2}\right) \quad , \qquad x = \frac{\bar{\alpha}_s}{N}$$

our result for $J/\Psi, \Upsilon$

$$1 + x(L - \log 4) + \frac{x^2}{6}\left(\pi^2 + 3\log^2 4 + 3L(L - \log 16)\right) + \cdots + \mathcal{O}(x^{10})$$

F_L – [Catani, Hautmann '94]

$\mu_F^2 = Q^2$

F_L: $\quad 1 - \frac{1}{3}\,x + 2.13\,x^2 + 2.27\,x^3 + 0.434\,x^4 + \ldots$

$J/\Psi, \Upsilon$: $\quad 1 - 1.39\,x + 2.61\,x^2 + 0.481\,x^3 - 4.96\,x^4 + \ldots$

$\mu_F^2 = Q^2/4$

F_L: $\quad 1 + 1.05\,x + 2.63\,x^2 + 5.35x^3 + 8.97\,x^4 + \ldots$

$J/\Psi, \Upsilon$: $\quad 1 + 0.\,x + 1.64\,x^2 + 3.21\,x^3 + 1.08\,x^4 + \ldots$

Some implementation for Υ photoproduction

$$\mathcal{I}m A^g \sim H^g(\xi,\xi) + \int\limits_{\xi}^{1} \frac{dx}{x} H^g(x,\xi) \sum_{n=1} C_n(L) \frac{\bar{\alpha}_s^n}{(n-1)!} \log^{n-1}\frac{x}{\xi}$$

without loss of accuracy $H^g(x,\xi) \to xg(x)$, but LO – $H^g(\xi,\xi)$ should be kept.
$C_n(L)$ - L^n polynomials we have calculated, $L = \log\frac{Q^2}{\mu_F^2}$
in the numerics below we used:

- – CTEQ6M PDFs
- for LO term: $x\,g(x) \to H^g(\xi,\xi)$ – Radyushkin DD model
- substitute the first term $(n=1)$ in the sum, by the exact NLO coefficient
- but
  we use fixed order NLO approach to μ_F evolution of gluon GPD

Comparison with ZEUS (96-07) 468 pb^{-1} data:

$$\sigma^{\gamma p\to\Upsilon(1S)p} = 160 \pm 51^{+48}_{-21}\ pb \quad \text{for} \quad <W>= 100\ \text{GeV}$$

$$\sigma^{\gamma p\to\Upsilon(1S)p} = 321 \pm 88^{+45}_{-114}\ pb \quad \text{for} \quad <W>= 180\ \text{GeV}$$

Input for our calculation:

$$m_b = 4.9\ \text{GeV}\,, \quad b_\Upsilon = 4.5\ \text{GeV}^{-2}$$

Our results:

$Q^2/4 < \mu_F^2 < Q^2$

$$\sigma^{LO}(100) = 214 \div 185\ pb\,, \quad \sigma^{res}(100) = 159 \div 144\ pb$$

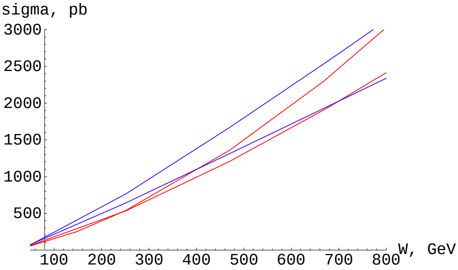
$$\sigma^{LO}(180) = 492 \div 358\ pb\,, \quad \sigma^{res}(180) = 427 \div 332\ pb$$

$Q^2/2 < \mu_F^2 < Q^2$

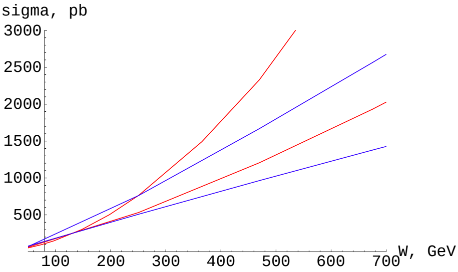
$$\sigma^{LO}(100) = 214 \div 202\ pb\,, \quad \sigma^{res}(100) = 159 \div 156\ pb$$

$$\sigma^{LO}(180) = 492 \div 430\ pb\,, \quad \sigma^{res}(180) = 345 \div 332\ pb$$

LO vs Resummed cross section



$100 \text{ GeV}^2 < \mu_F^2 < 50 \text{ GeV}^2$



$100 \text{ GeV}^2 < \mu_F^2 < 25 \text{ GeV}^2$

Summary

- GDPs enter factorization theorems for hard exclusive reactions in a similar manner as PDFs enter factorization theorem for DIS
- DVCS is a golden channel, a lot of new DVCS experiments planned - JLAB 12, COMPASS, EIC(?)
- GPDs in other exclusve processes - TCS, 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 are very important: large for TCS; dramatic for VM photoproduction.
- High energy resummation needed for VM photoproduction (in progress).