Probing GPDs in Ultraperipheral Collisions

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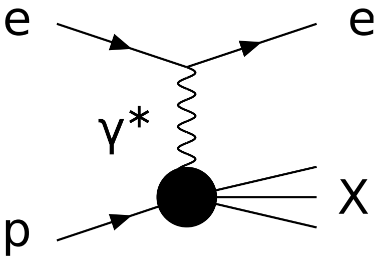
GDR PH-QCD Annual meeting
15-18 December 2014,Palaiseau

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



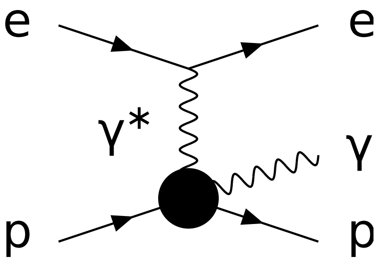
In the Björken limit i.e. when the photon virtality $Q^2 = -q^2$ and the squared hadronic c.m. energy $(p+q)^2$ become large, with the ratio $x_B = \frac{Q^2}{2p\cdot q}$ fixed, the cross section factorizes into a hard partonic subprocess calculable in the perturbation theory, and a parton distributions.

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.

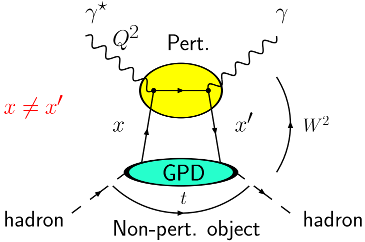
$$\begin{aligned} \text{DIS}: &\qquad \sigma = \text{PDF} \otimes \text{partonic cross section} \\ \text{DVCS}: &\qquad \mathcal{M} = \text{GPD} \otimes \text{partonic amplitude} \end{aligned}$$

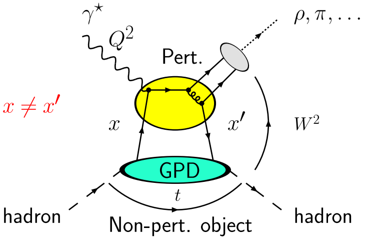
GPDs

- 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 - 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 ...

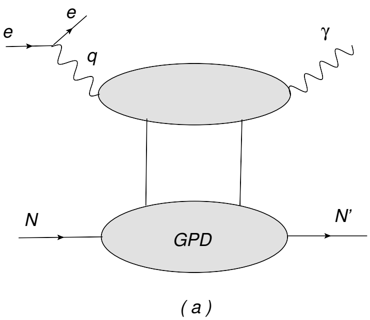


Figure : Deeply Virtual Compton Scattering (DVCS) : $lN \to l'N'\gamma$

we can also study timelike DVCS

Berger, Diehl, Pire, 2002

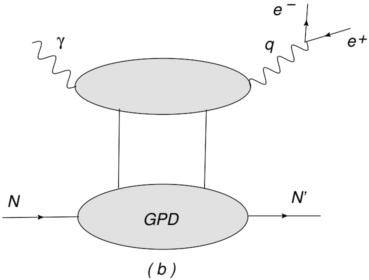


Figure : Timelike Compton Scattering (TCS): $\gamma N \to l^+ l^- N'$

Why TCS:

- universality of the GPDs
- another source for GPDs extraction - M.Boër talk yesterday, and M.Boër&M.Guidal: arXiv:1412.2036
- 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:

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

,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

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

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

- 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 NLO

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.

Compton Form Factors - DVCS - $Re(\mathcal{H})$

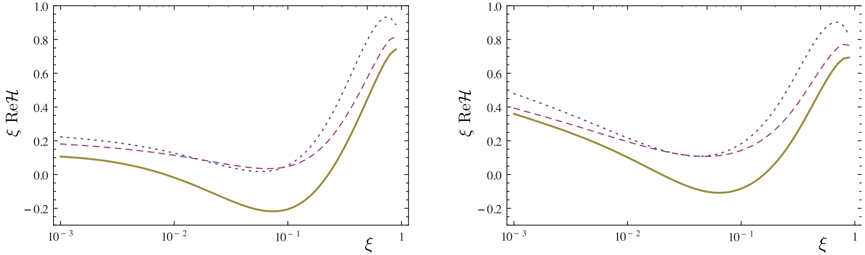


Figure : The real part of the *spacelike* Compton Form Factor $\mathcal{H}(\xi)$ multiplied by ξ, as a function of ξ in the double distribution model based on Kroll-Goloskokov (upper left) and MSTW08 (upper right) parametrizations, for $\mu_F^2 = Q^2 = 4\,\mathrm{GeV}^2$ and $t = -0.1\,\mathrm{GeV}^2$, at the Born order (dotted line), including the NLO quark corrections (dashed line) and including both quark and gluon NLO corrections (solid line).

Compton Form Factors - DVCS - $Im(\mathcal{H})$

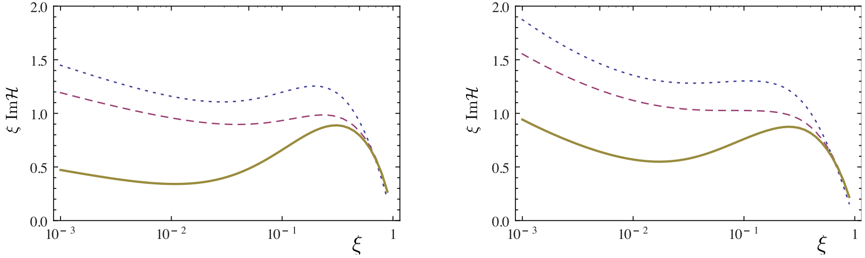


Figure : The imaginary part of the *spacelike* Compton Form Factor $\mathcal{H}(\xi)$ multiplied by ξ, as a function of ξ in the double distribution model based on Kroll-Goloskokov (upper left) and MSTW08 (upper right) parametrizations, for $\mu_F^2 = Q^2 = 4\,\mathrm{GeV}^2$ and $t = -0.1\,\mathrm{GeV}^2$, at the Born order (dotted line), including the NLO quark corrections (dashed line) and including both quark and gluon NLO corrections (solid line).

Few words about factorization scale (PRELIMINARY).

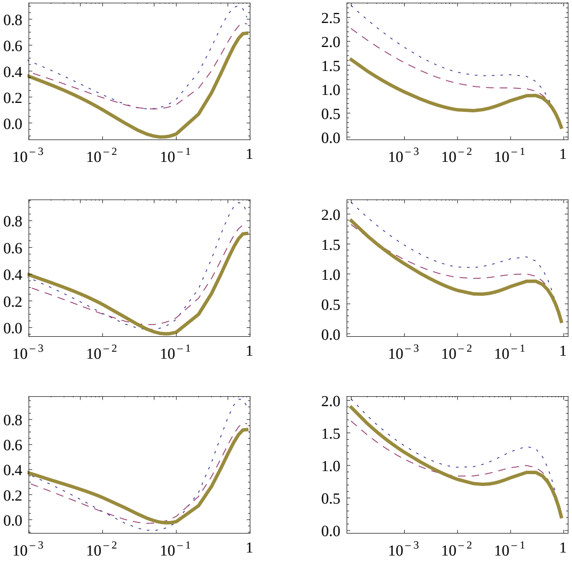


Figure : Left column - $Re(\mathcal{H}(\xi))$, right column - $Im(\mathcal{H}(\xi))$, $Q^2 = 4\,\mathrm{GeV}^2$, $\mu_F^2 = Q^2, Q^2/2, Q^2/3$

Few words about factorization scale (PRELIMINARY).

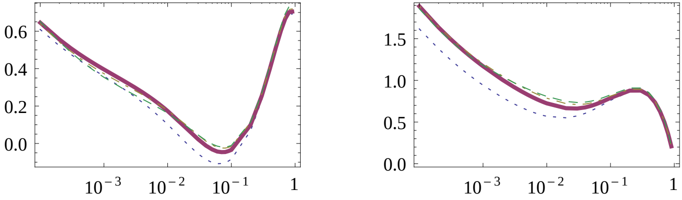


Figure : Full NLO result. Left column - $\xi \cdot Re(\mathcal{H}(\xi))$, right column - $\xi \cdot Im(\mathcal{H}(\xi))$, $Q^2 = 4\,\mathrm{GeV}^2$, $\mu_F^2 = Q^2, Q^2/2, Q^2/3$

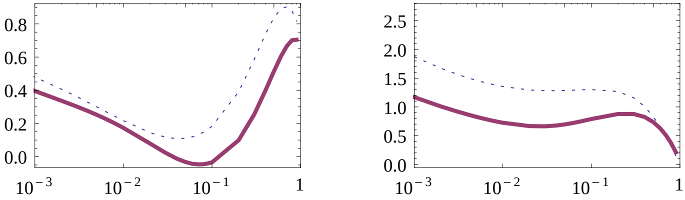


Figure : Left column - $\xi \cdot Re(\mathcal{H}(\xi))$, right column - $\xi \cdot Im(\mathcal{H}(\xi))$. Dotted - LO with $Q^2 = mu_F^2$, Solid NLO with $Q^2 = \mu_F^2/2$.

Compton Form Factors - TCS - $Re(\mathcal{H})$

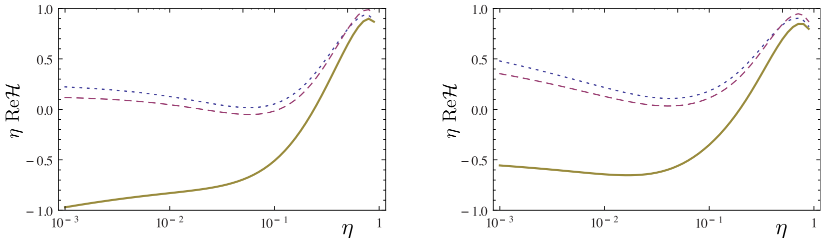


Figure : The real part of the *timelike* Compton Form Factor $\mathcal{H}$ multiplied by η, as a function of η in the double distribution model based on Kroll-Goloskokov (upper left) and MSTW08 (upper right) parametrizations, for $\mu_F^2 = Q^2 = 4$ GeV^2 and $t = -0.1$ GeV^2. Below the ratios of the NLO correction to LO result of the corresponding models.

Compton Form Factors - TCS - $Im(\mathcal{H})$

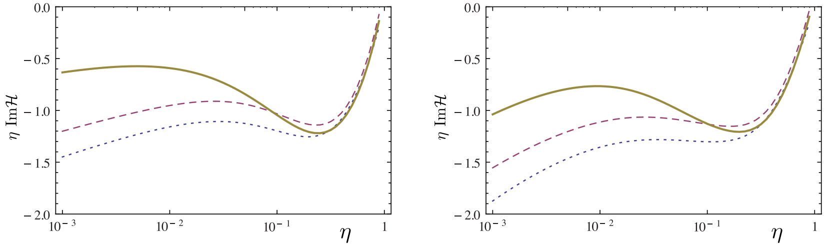


Figure : The imaginary part of the *timelike* Compton Form Factor $\mathcal{H}$ multiplied by η, as a function of η in the double distribution model based on Kroll-Goloskokov (upper left) and MSTW08 (upper right) parametrizations, for $\mu_F^2 = Q^2 = 4$ GeV^2 and $t = -0.1$ GeV^2. Below the ratios of the NLO correction to LO result of the corresponding models.

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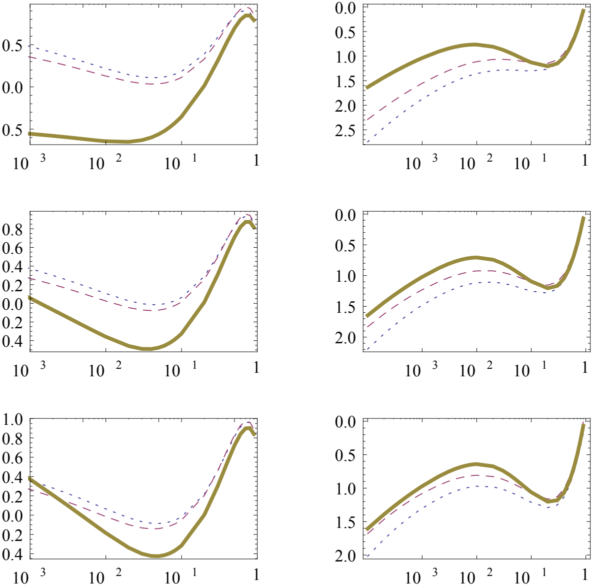

Figure : Left column - $Re(\mathcal{H}(\xi))$, right column - $Im(\mathcal{H}(\xi))$, $Q^2 = 4\,\mathrm{GeV}^2$, $\mu_F^2 = Q^2, Q^2/2, Q^2/3$

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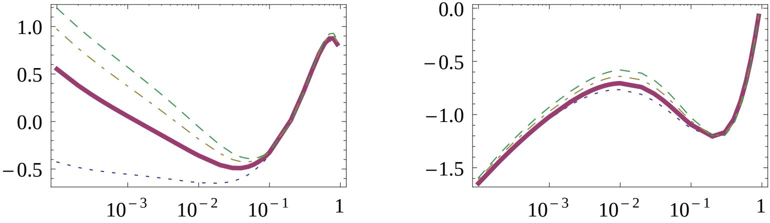

Figure : Full NLO result. Left column - $\xi \cdot Re(\mathcal{H}(\xi))$, right column - $\xi \cdot Im(\mathcal{H}(\xi))$, $Q^2 = 4\,\mathrm{GeV}^2$, $\mu_F^2 = Q^2, Q^2/2, Q^2/3$

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

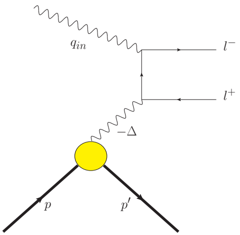

Figure : The Feynman diagram for the Bethe-Heitler amplitude.

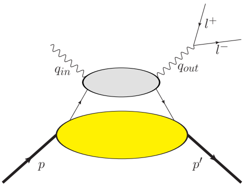

Figure : The Feynman diagram for the Compton amplitude.

TCS

Berger, Diehl, Pire, 2002

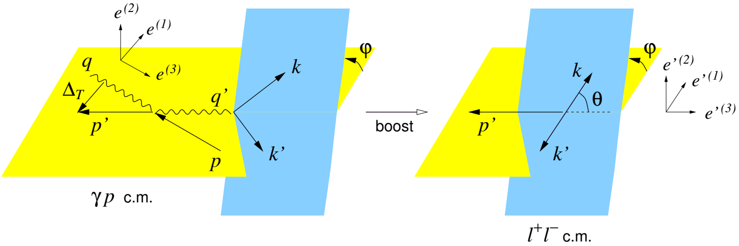

Figure : Kinematical variables and coordinate axes in the γp and $\ell^+\ell^-$ c.m. frames.

Interference

B-H dominant for not very high energies:

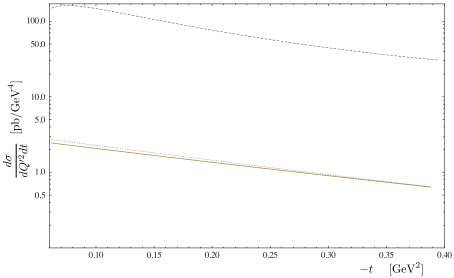

Figure : LO (dotted) and NLO (solid) TCS and Bethe-Heitler (dash-dotted) contributions to the cross section as a function of t for $Q^2 = \mu^2 = 4\,\mathrm{GeV}^2$ integrated over $\theta \in (\pi/4; 3\pi/4)$ and over $\phi \in (0; 2\pi)$ for $E_\gamma = 10\,\mathrm{GeV}(\eta \approx 0.11)$.

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

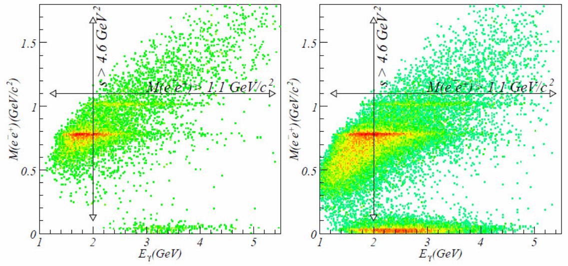

Figure : e^+e^- invariant mass distribution vs quasi-real photon energy. For TCS analysis $M(e^+e^-) > 1.1\,\mathrm{GeV}$ and $s_{\gamma p} > 4.6\,\mathrm{GeV}^2$ regions are chosen. Left graph represents e1-6 data set, right one is from e1f data set.

Theory vs experiment

R.Paremuzyan and V.Guzey:

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

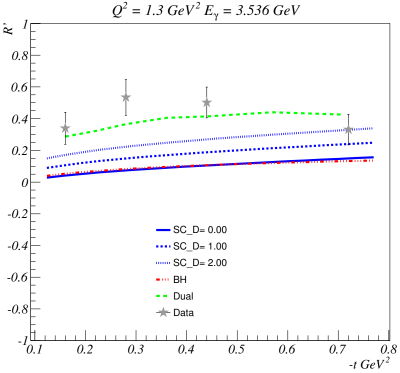

Figure : Thoeretical prediction of the ratio R for various GPDs models. Data points after combining both e1-6 and e1f data sets.

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

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.

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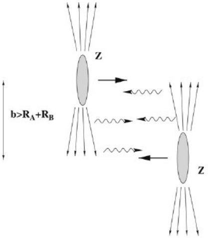
[2] *Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606*
[3] *Yerevan Physics Institute, 375036 Yerevan, Armenia*
[4] *Institut de Physique Nucleaire d'Orsay, IN2P3, BP 1, 91406 Orsay, France*
[5] *Hampton University, Hampton, Virginia 23668*
[6] *Ohio University, Athens, Ohio 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 cross section at UPC

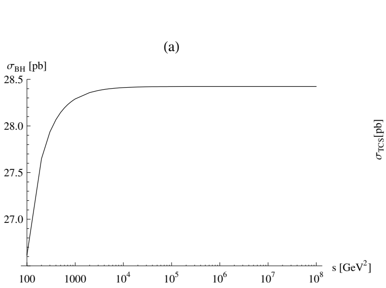


Figure : (a) The BH cross section integrated over $\theta \in [\pi/4, 3\pi/4]$, $\varphi \in [0, 2\pi]$, $Q'^2 \in [4.5, 5.5]\,\mathrm{GeV}^2$, $|t| \in [0.05, 0.25]\,\mathrm{GeV}^2$, as a function of γp c.m. energy squared s. (b) σ_{TCS} as a function of γp c.m. energy squared s, for GRVGJR2008 NLO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

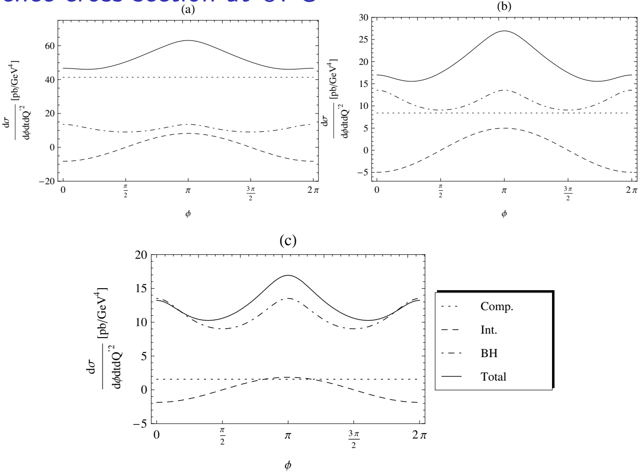


Figure : The differential cross sections (solid lines) for $t = -0.2\,\mathrm{GeV}^2$, ${Q'}^2 = 5\,\mathrm{GeV}^2$ and integrated over $\theta = [\pi/4, 3\pi/4]$, as a function of φ, for $s = 10^7\,\mathrm{GeV}^2$ (a), $s = 10^5\,\mathrm{GeV}^2$(b), $s = 10^3\,\mathrm{GeV}^2$ (c) with $\mu_F^2 = 5\,\mathrm{GeV}^2$. 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 ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)

UPC in the fixed target mode - AFTER@LHC

work in progress with J.-P. Lansberg and L.Szymanowski

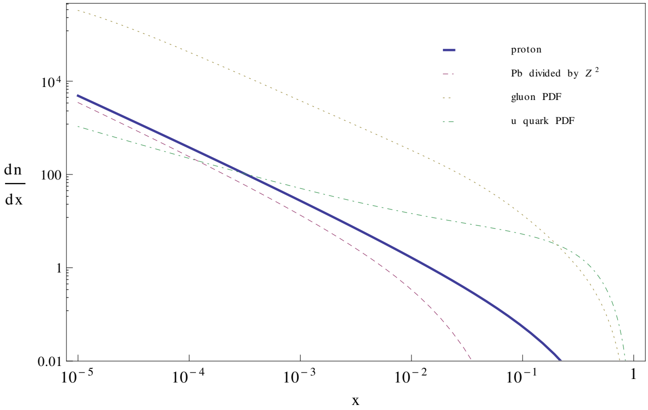
- $\gamma_{\rm lab}^{\rm beam} \simeq 7000$ ($E_p = 7000$ GeV)
- $E_\gamma^{\rm max} \simeq \gamma_{\rm lab}^{\rm beam} \times 30$ MeV ($1/(R_{\rm Pb} + R_p) \simeq 30$ MeV)
- $\sqrt{s_{\gamma p}} = \sqrt{2 m_p E_\gamma}$ up to 20 GeV
- No pile-up

System	target thickness (cm)	$\sqrt{s_{NN}}$ (GeV)	$\mathcal{L}_{AB}$[a] ($\mathrm{pb}^{-1}\mathrm{yr}^{-1}$)	$E_A^{\rm lab}$ (GeV)	$E_B^{\rm lab}$ (GeV)	$\gamma^{\rm c.m.s.}$ ($\frac{\sqrt{s_{NN}}}{2m_N}$)	$\gamma^{A\leftrightarrow B}$ ($\frac{s_{NN}}{2m_N^2}$)	$\frac{\hbar c}{R_A+R_B}$ (MeV)	$E_{\gamma\ \rm max}^{A/B\ \rm rest}$ (GeV)	$\sqrt{s_{\gamma N}^{\rm max}}$ (GeV)	$E_{\gamma\ \rm max}^{\rm c.m.s.}$ (GeV)	$\sqrt{s_{\gamma\gamma}^{\rm max}}$ (GeV)
AFTER												
pp	100	115	2.0×10^4	7000	m_N	61.2	7450	140	1050	44	8.5	17
pPb	1	115	1.6×10^2	7000	m_N	61.2	7450	26	190	19	1.6	3.2
pd	100	115	2.4×10^4	7000	m_N	61.2	7450	70	520	31	4.3	8.5
PbPb	1	72	$7.\times10^{-3}$	2760	m_N	38.3	2940	14	40	9	0.5	1.0
Pbp	100	72	1.1	2760	m_N	38.3	2940	26	76	12	1.0	2.0
Arp	100	77	1.1	3150	m_N	40.9	3350	41	140	16	1.7	3.4
Op	100	81	1.1	3500	m_N	43.1	3720	52	190	19	2.2	4.5
RHIC												
pp	N/A	200	1.2×10^1	100	100	106.4	22600	140	3150	77	15	30
AuAu	N/A	200	2.8×10^{-3}	100	100	106.4	22600	14	320	24	1.5	3.0
SPS												
InIn	.	17	.	160	m_N	9.22	170	17	2.9	2.5	0.15	0.31
PbPb	.	17	.	160	m_N	9.22	170	14	2.4	2.1	0.13	0.26

[a] For Arp and Op luminosity with AFTER, we conservatively assumed the same extracted flux of Ar and O as for Pb, *i.e.* 2×10^5 Pb/s.

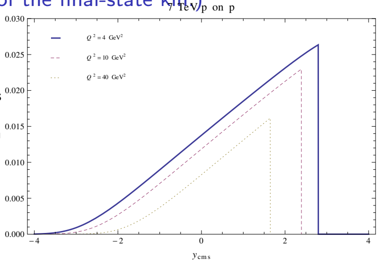
Attempt at CERN-SPS: "In-In Ultra Peripheral Collisions in NA60" by P. Ramalhete (PhD), 2009

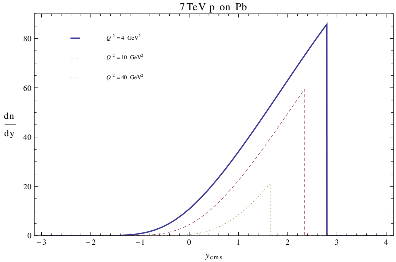
A closer look at the photon flux (as fct of the final-state kin.)

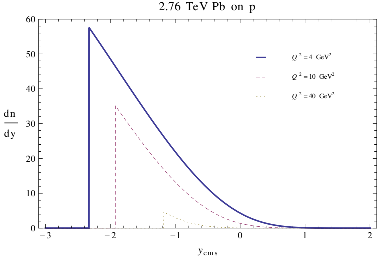


A closer look at the photon flux (as fct of the final-state kin.)

Let's look at the photoproduction of a dilepton, $\gamma p \to \ell^+ \ell^- p$, at small t and fixed dilepton mass (Q);
the dilepton rapidity depends on the incident photon energy:
$\frac{d\sigma^{hh}}{dy} = \frac{dn}{dy}\, d\sigma^{\gamma h}(s^{\gamma\ h}(k_\gamma(y)))$
$\Rightarrow$ let's look at the γ flux as a function of y



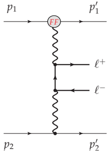




$y_{\rm Lab} = y_{\rm cms} + 4.8(4.3)$ for 7 TeV (2.76 TeV) beam

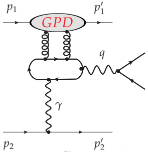
$\Rightarrow$ $Pb p$ is preferred with an acceptance $y_{\rm Lab} \in [2:5]$

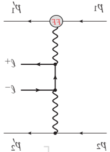
Timelike Compton Scattering vs. Bethe Heitler pair production



- Bethe Heitler ($\gamma p \to \ell\ell p$)
  [Should coincide with EPA $\otimes \gamma\gamma \to \ell^+\ell^-$]

$$\frac{d\sigma_{BH}^{\gamma p}}{dQ^2\, dt\, d(\cos\theta)\, d\varphi} \approx$$
$$\frac{\alpha_{em}^3}{2\pi s^2}\, \frac{1}{-t}\, \frac{1+\cos^2\theta}{\sin^2\theta} \times \left[\left(F_1^2 - \frac{t}{4M^2} F_2^2 \right) \frac{2}{\tau^2}\, \frac{\Delta_T^2}{-t} + (F_1 + F_2)^2 \right]$$





- Interference with Timelike Compton Scattering

$$\frac{d\sigma_{INT}^{\gamma p}}{dQ^2\, dt\, d(\cos\theta)\, d\varphi} \approx$$
$$-\frac{\alpha_{em}^3}{4\pi s^2}\, \frac{\sqrt{t_0 - t}}{-tQ}\, \frac{\sqrt{1-\eta^2}}{\eta} \left(\cos\varphi\, \frac{1+\cos^2\theta}{\sin\theta} \right) \mathrm{Re} \left[F_1 \mathcal{H} - \eta (F_1 + F_2)\, \tilde{\mathcal{H}} - \frac{t}{4M^2}\, F_2\, \mathcal{E} \right]$$

where $\{\mathcal{H}, \tilde{\mathcal{H}}, \mathcal{E}\}(\eta, t) = \int_{-1}^{1} dx\, T(x, \eta)\, \{H, \tilde{H}, E\}(x, \eta, t)$

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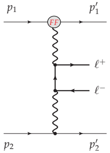

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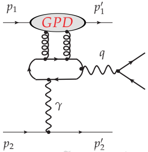

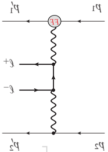

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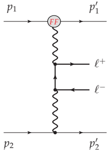

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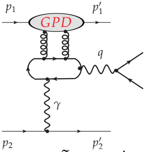

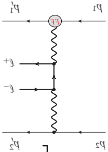

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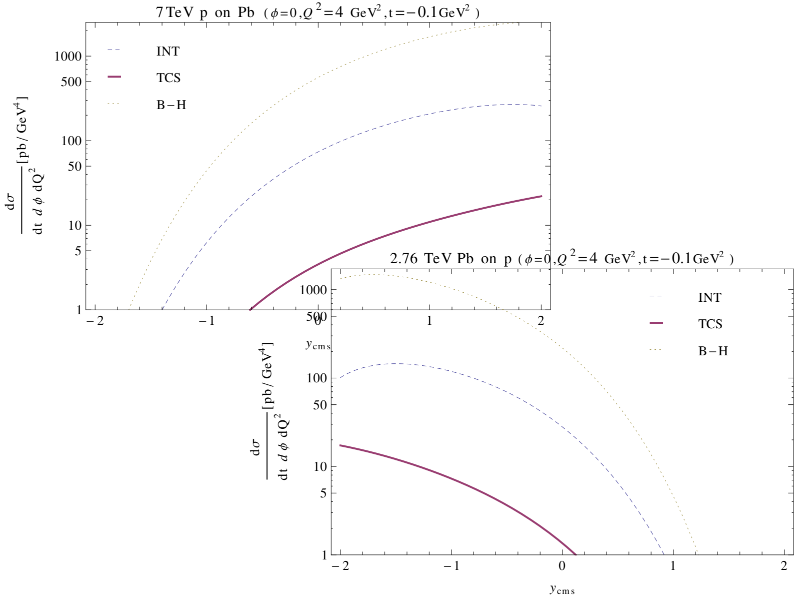
First results for $\sigma^{p\mathrm{Pb}}$ and $\sigma^{\mathrm{Pb}p}$



Gluon GPDs in the UPC production of heavy mesons

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

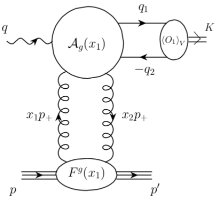


Figure 1: Kinematics of heavy vector meson photoproduction.

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:

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

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

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

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

- LO

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

- 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

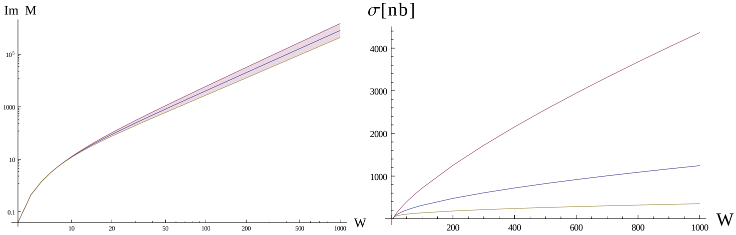


Figure : (left) Imaginary part of the amplitude $\mathcal{M}$ and (right) photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$.

Photoproduction amplitude and cross section - LO and NLO.

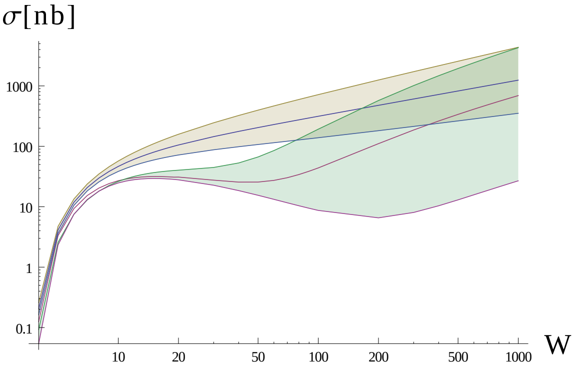


Figure : Photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$- LO and NLO

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?,...?)

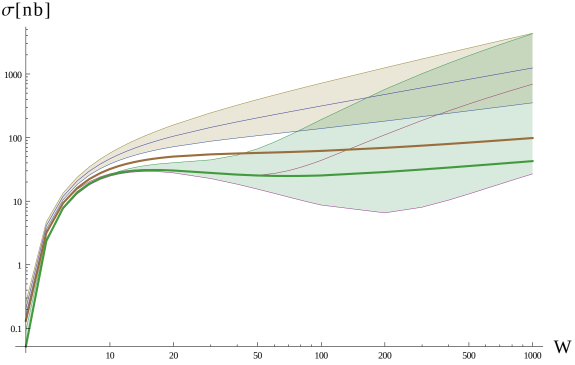
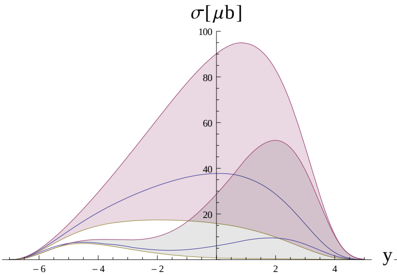
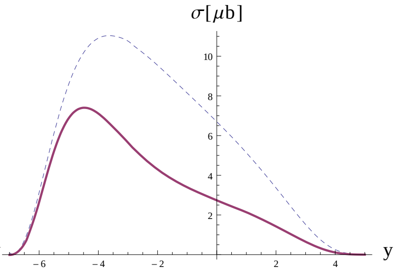


Figure : Photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$- LO and NLO. Thick lines for LO and NLO for $\mu_F^2 = 1/4 M_{J/\psi}^2$.

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).