

Hard photoproduction of a diphoton with a large invariant mass

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Plan of presentation

- ▶ Hard photoproduction of a diphoton with a large invariant mass;
 - ▶ GPDs and Goloskokov–Kroll model of the GPDs;
 - ▶ Kinematics;
 - ▶ Differential cross section;
- ▶ Further research;
 - ▶ Electroproduction (Bethe–Heitler process with two–photon emission);
 - ▶ Photoproduction of a diphoton in NLO.



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Hard photoproduction of a diphoton with a large invariant mass

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The electromagnetic probe has proven to be a very efficient way to access the three-dimensional structure of the nucleon, particularly thanks to the exclusive Compton processes. We explore the hard photoproduction of a large invariant mass diphoton in the kinematical regime where the diphoton is nearly forward and its invariant mass is the hard scale enabling to factorize the scattering amplitude in terms of generalized parton distributions. We calculate unpolarized cross sections and the angular asymmetry triggered by a linearly polarized photon beam.

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I. INTRODUCTION

The last twenty years have witnessed a tremendous progress in the understanding of hard exclusive scattering in the framework of the QCD collinear factorization of hard amplitudes in specific kinematics in terms of generalized parton distributions (GPDs) and hard perturbatively calculable coefficient functions [1,2].

In this paper, we study the exclusive photoproduction of two photons on a unpolarized proton or neutron target

$$v^\mu = an^\mu + bp^\mu + v_\perp^\mu, \quad (2)$$

with p and n the light-cone vectors

$$p^\mu = \frac{\sqrt{s}}{2}(1, 0, 0, 1), \quad n^\mu = \frac{\sqrt{s}}{2}(1, 0, 0, -1), \quad p \cdot n = \frac{s}{2}, \quad (3)$$



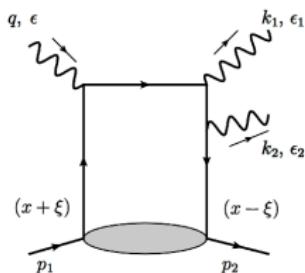
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$$\gamma(q, \epsilon) + N(p_1, \lambda) \rightarrow \gamma_1(k_1, \epsilon_1) + \gamma_2(k_2, \epsilon_2) + N'(p_2, \lambda')$$

Analysis of this process:



- ▶ the hard part is a pure electromagnetic process;
- ▶ is the $2 \rightarrow 3$ process which gives independent information about the GPDs;
- ▶ let us to give an answer if factorization exists (or not) in this kind of $2 \rightarrow 3$ processes;

Large invariant mass $M_{\gamma\gamma}$: $2.10 \text{ GeV}^2 \leq M_{\gamma\gamma}^2 \leq 9.47 \text{ GeV}^2$

Small momentum transfer $t = (p_2 - p_1)^2$: $-0.5 \text{ GeV}^2 \leq t_{min}(M_{\gamma\gamma}^2) \leq 0$

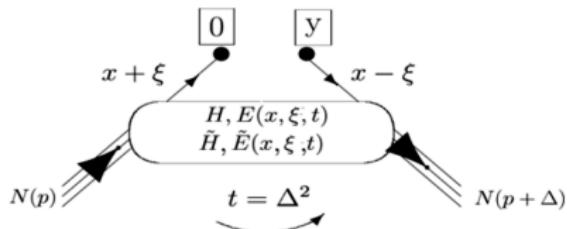


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GPDs

General Parton Distributions



Connection with PDFs

$$H^q(x, 0, 0) = \begin{cases} q(x), & x > 0 \\ -\bar{q}(-x), & x < 0 \end{cases}$$

$$\tilde{H}^q(x, 0, 0) = \begin{cases} \Delta q(x), & x > 0 \\ \Delta \bar{q}(-x), & x < 0 \end{cases}$$

Connection with FFs

$$\int_{-1}^{+1} dx H^q(x, \xi, t) = F_1^q(t),$$

$$\int_{-1}^{+1} dx E^q(x, \xi, t) = F_2^q(t),$$

$$\int_{-1}^{+1} dx \tilde{H}^q(x, \xi, t) = G_A^q(t),$$

$$\int_{-1}^{+1} dx \tilde{E}^q(x, \xi, t) = G_P^q(t),$$

$$\frac{P^+}{2\pi} \int dy^- e^{ixP^+y^-} \langle p' | \bar{\psi}_q(0) \gamma^+ \psi_q(y) | p \rangle |_{y^+ = y_\perp = 0} =$$

$$= H^q(x, \xi, t) \bar{N}(p') \gamma^+ N(p) + E^q(x, \xi, t) \bar{N}(p') i \sigma^{+\nu} \frac{\Delta_\nu}{2m_N} N(p),$$

$$\frac{P^+}{2\pi} \int dy^- e^{ixP^+y^-} \langle p' | \bar{\psi}_q(0) \gamma^+ \gamma^5 \psi_q(y) | p \rangle |_{y^+ = y_\perp = 0} =$$

$$= \tilde{H}^q(x, \xi, t) \bar{N}(p') \gamma^+ \gamma_5 N(p) + \tilde{E}^q(x, \xi, t) \bar{N}(p') \gamma_5 \frac{\Delta^+}{2m_N} N(p)$$



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The Goloskokov–Kroll model of the GPDs

Let $F = \{H, E, \tilde{H}, \tilde{E}\}$

$$F^i(x, \xi, t) = \int_{-1}^1 d\rho \int_{-1+|\rho|}^{1-|\rho|} d\eta \delta(\rho + \xi\eta - x) f_i(\rho, \eta, t) + D_i(x, t) \theta(\xi^2 - x^2)$$

f_i is a double distribution, D_i is a D-term, $i = \text{gluon, sea, val.}$

$$f_i(\rho, \eta, t) = F^i(\rho, \xi = 0, t) \omega_i(\rho, \eta)$$

where

$$\omega_i(\rho, \eta) = \frac{\Gamma(2n_i + 2)}{2^{2n_i+1} \Gamma^2(n_i + 1)} \frac{((1 - |\rho|^2) - \eta^2)^{n_i}}{(1 - |\rho|)^{2n_i+1}}, \quad \int_{-1+|\rho|}^{1-|\rho|} d\eta \omega_i(\rho, \eta) = 1.$$

$$F^i(\rho, \xi = 0, t) = F^i(\rho, \xi = 0, t = 0) \exp(tp_f(\rho))$$

where $p_f(\rho) = -\alpha'_f \ln \rho + b_f$.

$$D_i(x, t) = 0$$

$$n_i = \begin{cases} 1 & \text{for } i = \text{val} \\ 2 & \text{for } i = \text{sea, g} \end{cases}$$

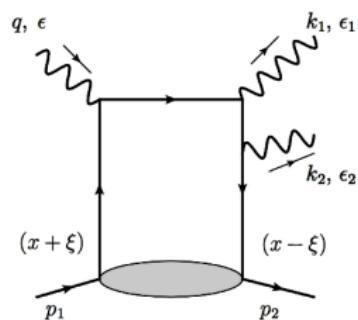
P. Kroll, H. Moutarde and F. Sabatié, Eur. Phys. J. C 73, 2278 (2013)

The parameters have been obtained from a fit to the CTEQ6M PDFs
(J. Pumplin et al. J. High Energy Phys. 0207, 012 (2002))



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Sudakov basis

$$\begin{aligned}v^\mu &= an^\mu + bp^\mu + v_\perp^m u; \\p &= \frac{\sqrt{s}}{2}(1, 0, 0, 1), \\n &= \frac{\sqrt{s}}{2}(1, 0, 0, -1), \\p \cdot n &= \frac{s}{2}\end{aligned}$$

Mandelstam invariants:

$$\begin{aligned}t &= (p_2 - p_1)^2, \\M_{\gamma\gamma}^2 &= (k_1 + k_2)^2 \\-u' &= -(k_2 - q)^2\end{aligned}$$

$$\begin{aligned}p_1^\mu &= (1 + \xi)p^\mu + \frac{M^2}{s(1+\xi)}n^\mu, & p_2^\mu &= (1 - \xi)p^\mu + \frac{M^2 - \Delta_\perp^2}{s(1-\xi)}n^\mu + \Delta_\perp^\mu, & q^\mu &= n^\mu \\k_1^\mu &= \alpha_1 n^\mu + \frac{\left(\frac{p_\perp - \Delta_\perp}{2}\right)^2}{\alpha_1 s}p^\mu + p_\perp^\mu - \frac{\Delta_\perp^\mu}{2} \\k_2^\mu &= \alpha_2 n^\mu + \frac{\left(\frac{p_\perp + \Delta_\perp}{2}\right)^2}{\alpha_2 s}p^\mu - p_\perp^\mu - \frac{\Delta_\perp^\mu}{2}\end{aligned}$$



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Differential Cros section

$$\frac{d\sigma}{dM_{\gamma\gamma}^2 dt d(-u')} = \frac{1}{2} \frac{1}{(2\pi)^3 32 S_{\gamma N}^2 M_{\gamma\gamma}^2} \sum_{\lambda_i, \lambda_f, \lambda'_f, s_1, s_2} \frac{|\tau|^2}{4},$$

$$S_{\gamma N} = (q + p_1)^2, \quad -u' = -(k_2 - q)^2$$

Independent kinematical variables $\{t, u', M_{\gamma\gamma}^2\}$,
where

$$\begin{aligned} \tau &= \frac{1}{4} \int_{-1}^1 dx \sum_q \int dz^- e^{ixz^- P^+} \langle P_2 | \bar{\psi}_q \left(-\frac{z}{2}\right) [CF_q^V \not{h} + CF_q^A \not{h} \gamma^5] \psi_q \left(\frac{z}{2}\right) | P_1 \rangle = \\ &= \frac{1}{2} \frac{1}{2P^+} \int_{-1}^1 dx \sum_q [CF_q^V(x, \xi) (H^q(x, \xi) \bar{U}(p_2) \not{h} U(p_1) + \\ &\quad + E^q(x, \xi) \bar{U}(p_2) \frac{i\sigma^{\mu\nu}\Delta_\nu n_\mu}{2M} U(p_1)) + \\ &\quad + CF_q^A(x, \xi) (\tilde{H}^q(x, \xi) \bar{U}(p_2) \not{h} \gamma^5 U(p_1) + \tilde{E}^q(x, \xi) \bar{U}(p_2) \frac{i\gamma_5(\Delta \cdot n)}{2M} U(p_1))] \end{aligned}$$



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Vector Coefficient Function:

$$iCF_q^V = -ie_q^3 \left[A^V \left(\frac{1}{D_1(x)D_2(x)} + \frac{1}{D_1(-x)D_2(-x)} \right) + B^V \left(\frac{1}{D_1(x)D_3(x)} + \frac{1}{D_1(-x)D_3(-x)} \right) + C^V \left(\frac{1}{D_2(x)D_3(-x)} + \frac{1}{D_2(-x)D_3(x)} \right) \right]$$

where $e_q = Q_q|e|$ ($|e|$ is absolute value of electron charge).

Where:

$$D_1(x) = s(x + \xi + i\varepsilon)$$

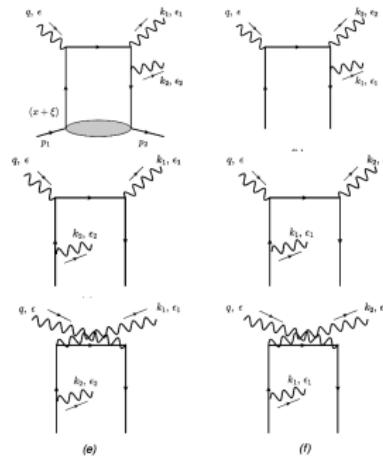
$$D_2(x) = s\alpha_2(x - \xi + i\varepsilon)$$

$$D_3(x) = s\alpha_1(x - \xi + i\varepsilon)$$

$$V_{k_1} = (\epsilon_\perp(q) \cdot \epsilon_\perp^*(k_1))(p_\perp \cdot \epsilon_\perp^*(k_2))$$

$$V_{k_2} = (\epsilon_\perp(q) \cdot \epsilon_\perp^*(k_2))(p_\perp \cdot \epsilon_\perp^*(k_1))$$

$$V_p = (\epsilon_\perp^*(k_1) \cdot \epsilon_\perp^*(k_2))(p_\perp \cdot \epsilon_\perp(q))$$



$$A^V = 2s(V_{k_1} - V_p + \frac{1}{\alpha_1}V_{k_2})$$

$$B^V = 2s(-V_{k_2} + V_p - \frac{1}{\alpha_2}V_{k_1})$$

$$C^V = 2s((\alpha_2 - \alpha_1)V_p + V_{k_2} - V_{k_1})$$



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Axial Coefficient Function:

$$iCF_q^A = -ie_q^3 \left[A^A \left(\frac{1}{D_1(x)D_2(x)} - \frac{1}{D_1(-x)D_2(-x)} \right) + B^A \left(\frac{1}{D_1(x)D_3(x)} - \frac{1}{D_1(-x)D_3(-x)} \right) \right]$$

where $e_q = Q_q|e|$ ($|e|$ is absolute value of electron charge).

Where:

$$D_1(x) = s(x + \xi + i\varepsilon)$$

$$A^A = 4i \left(A_{k_1} + \frac{1}{\alpha_1} A_{k_2} - A_p \right)$$

$$D_2(x) = s\alpha_2(x - \xi + i\varepsilon)$$

$$B^A = 4i \left(-\frac{1}{\alpha_2} A_{k_1} - A_{k_2} + A_p \right)$$

$$D_3(x) = s\alpha_1(x - \xi + i\varepsilon)$$

$$A_{k_1} = (p_\perp \cdot \epsilon_\perp^*(k_2)) e^{pn\epsilon_\perp(q)\epsilon_\perp^*(k_1)}$$

$$A_{k_2} = (p_\perp \cdot \epsilon_\perp^*(k_1)) e^{pn\epsilon_\perp(q)\epsilon_\perp^*(k_2)}$$

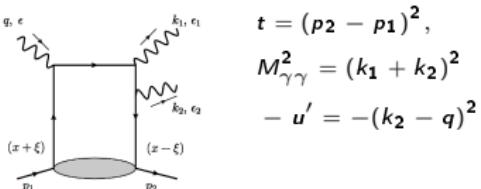
$$A_p = (\epsilon_\perp^*(k_1) \cdot \epsilon_\perp^*(k_2)) e^{pn\epsilon_\perp(q)p_\perp}$$



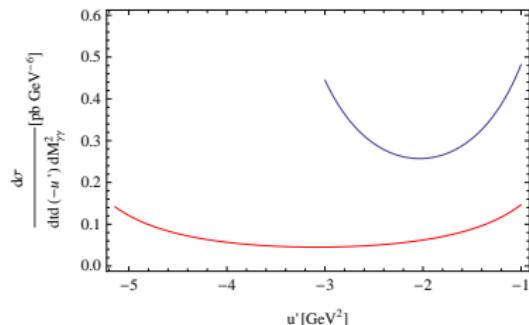
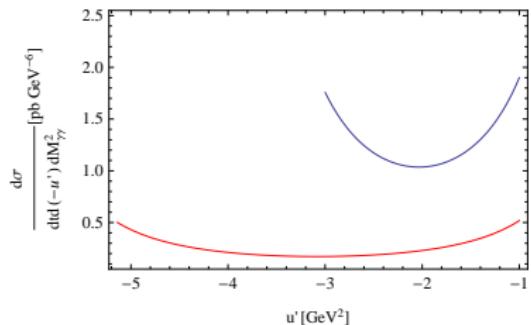
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Unpolarized differential cross section

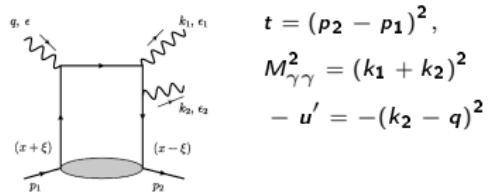


The u' dependence of the unpolarized differential cross section $\frac{d\sigma}{dM_{\gamma\gamma}^2 du'/dt}$ at $t = t_{min}$ and $S_{\gamma N} = 20$ GeV 2 for $M_{\gamma\gamma}^2 = 4$ GeV 2 (blue upper curve) and for $M_{\gamma\gamma}^2 = 6$ GeV 2 (red lower curve), for a proton target (left panel) and neutron target (right panel).

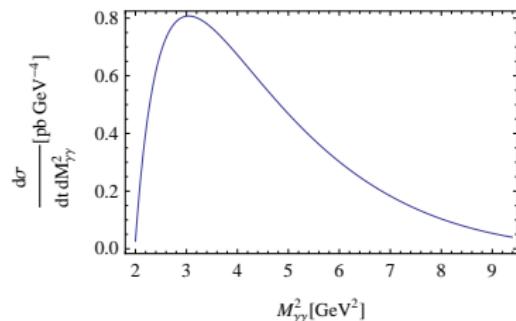
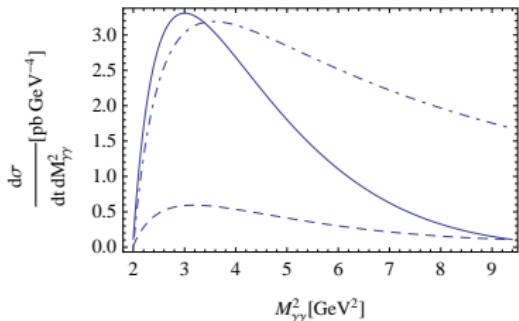


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Unpolarized differential cross section



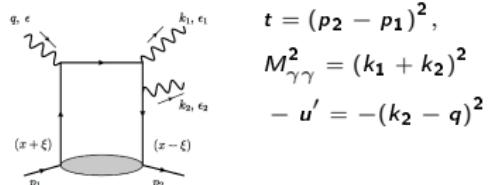
The $M_{\gamma\gamma}^2$ dependence of the unpolarized differential cross section on a proton (left panel) and on a neutron (right panel) at $t = t_{min}$ and $S_{\gamma N} = 20$ GeV 2 (full curves), $S_{\gamma N} = 100$ GeV 2 (dashed curve) and $S_{\gamma N} = 10^6$ GeV 2 (dash-dotted curve, multiplied by 10^5).



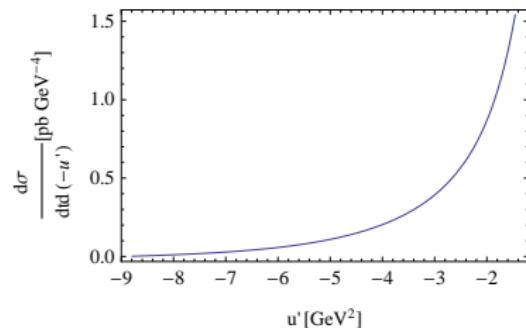
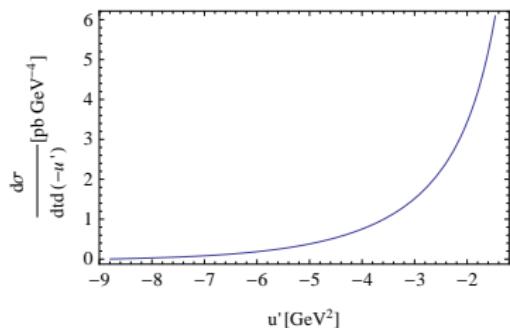
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Unpolarized differential cross section



The u' dependence of the unpolarized differential cross section on a proton (left panel) and on a neutron (right panel) at $t = t_{\min}$ and $S_{\gamma N} = 20 \text{ GeV}^2$ integrated over $M_{\gamma\gamma}^2$.

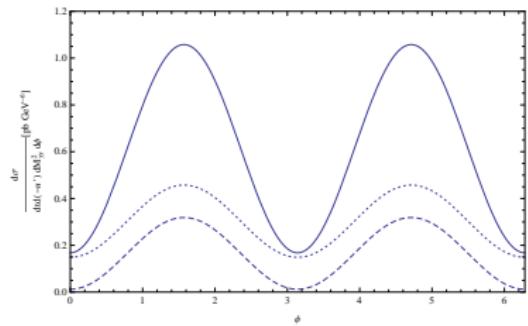


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Polarized differential cross section



Azimuthal dependence of the differential cross section at $t = t_{min}$ and $S_{\gamma N} = 20 \text{ GeV}^2$. $(M_{\gamma\gamma}^2, u') = (3, -2) \text{ GeV}^2$ (solid line), $(M_{\gamma\gamma}^2, u') = (4, -1) \text{ GeV}^2$ (dotted line), $(M_{\gamma\gamma}^2, u') = (4, -2) \text{ GeV}^2$. ϕ is the angle between the initial photon polarization and one of the final photon momentum in the transverse plane

$$t = (\mathbf{p}_2 - \mathbf{p}_1)^2,$$
$$M_{\gamma\gamma}^2 = (k_1 + k_2)^2$$
$$-u' = -(k_2 - q)^2$$
$$k_1^\mu = \alpha_1 n^\mu + \frac{(\mathbf{p}_\perp)^2}{\alpha_1 s} p^\mu + \mathbf{p}_\perp^\mu$$
$$k_2^\mu = \alpha_2 n^\mu + \frac{(\mathbf{p}_\perp)^2}{\alpha_2 s} p^\mu - \mathbf{p}_\perp^\mu$$

$$\epsilon(q) = (0, 1, 0, 0)$$

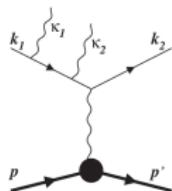
$$p_\perp = (0, p_T \cos \phi, p_T \sin \phi, 0)$$

$$\frac{d\sigma_I}{dM_{\gamma\gamma}^2 dt d(-u') d\phi} = \frac{1}{2} \frac{1}{(2\pi)^4 32 S_{\gamma M}^2 M_{\gamma\gamma}^2} \sum_{\lambda_1, \lambda_2, s_1, s_2} \frac{|\tau|^2}{2}$$



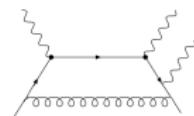
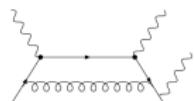
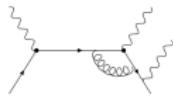
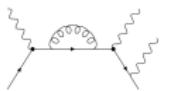
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Hard photoproduction of a diphoton with a large invariant mass. Further research.



- ▶ Electroproduction (Bethe–Heitler processes of two photon production)

$$\mathcal{T} = |\mathcal{T}_{\gamma\gamma} + \mathcal{T}_{BH}|^2 = |\mathcal{T}_{\gamma\gamma}|^2 + |\mathcal{T}_{BH}|^2 + \mathcal{I}$$



- ▶ Next to Leading Order calculations (QCD factorization)



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Conclusions

- ▶ The unpolarized cross sections and the angular asymmetry triggered by a linearly polarized photon beam for a hard photoproduction of diphoton with large invariant mass have been calculated (the new observables);
- ▶ This is interesting process from experimental point of view (planned experiment in JLab: CLAS or GlueX);
- ▶ We plan to extend analysis to electroproduction (Bethe–Heitler processes of two photon production);
- ▶ We plan to calculate the NLO (the QCD factorizations in this kind of processes).



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Conclusions

- ▶ The unpolarized cross sections and the angular asymmetry triggered by a linearly polarized photon beam for a hard photoproduction of diphoton with large invariant mass have been calculated (the new observables);
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Thank You!



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The Goloskokov–Kroll model of the GPDs

Parametrization of the GPD H

$$F^i(\rho, \xi = 0, t = 0) = H^i(\rho, \xi = 0, t = 0) = \rho^{-\delta_i} (1 - \rho)^{2n_i + 1} \sum_{j=0}^3 c_{ij} \rho^{j/2}$$

	<i>gluon</i>	<i>strange</i>	<i>u_val</i>	<i>d_val</i>
δ	$0.10 + 0.06L - 0.0027L^2$	$1.10 + 0.06L - 0.0027L^2$	0.48	0.48
α'	0.15 GeV^{-2}	0.15 GeV^{-2}	0.9 GeV^{-2}	0.9 GeV^{-2}
c_0	$2.23 + 0.362L$	$0.123 + 0.0003L$	$1.52 + 0.248L$	$0.76 + 0.248L$
c_1	$5.43 - 7.00L$	$-0.327 - 0.004L$	$2.88 - 0.940L$	$3.11 - 1.36L$
c_2	$-34.0 + 22.5L$	$0.692 - 0.068L$	$-0.095L$	$-3.99 + 1.15L$
c_3	$40.6 - 21.6L$	$-0.486 + 0.038L$	0	0

$$L = \ln \frac{Q^2}{Q_0^2} \text{ where } Q_0^2 = 4 \text{ GeV}^2$$

$$b_g = b_{sea} = 2.58 \text{ GeV}^{-2} + 0.25 \text{ GeV}^{-2} \ln \frac{m^2}{Q^2 + m^2}, \quad b_{val} = 0$$

where m is a proton mass.

$$\begin{aligned} f_{val}^q(\rho, \eta, t) &= (f^q(\rho, \eta, t) + f^q(-\rho, \eta, t)) \Theta(\rho) \\ f_{sea}^q(\rho, \eta, t) &= f^q(\rho, \eta, t) \Theta(\rho) - f^q(-\rho, \eta, t) \Theta(-\rho) \end{aligned}$$

$$H_{sea}^u = H_{sea}^d = \kappa_s H_{sea}^s, \quad \kappa_s = 1 + 0.68 / (1 + 0.52 \ln Q^2 / Q_0^2)$$

The parameters have been obtained from a fit to the CTEQ6M PDFs

(J. Pumplin et al. J. High Energy Phys. 0207, 012 (2002))



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The Goloskokov–Kroll model of the GPDs

Parametrization of the GPD E

$$\begin{aligned}E_{val}^q(\rho, \xi = 0, t = 0) &= B^{-1}(1 - \alpha_{val}, 1 + \beta_{val}^q) \kappa_q \rho^{-\alpha_{val}} (1 - \rho)^{\beta_{val}^q} \\E^s(\rho, \xi = 0, t = 0) &= N_s \rho^{-1-\delta_g} (1 - \rho)^{\beta_{Es}} \\E^g(\rho, \xi = 0, t = 0) &= N_g \rho^{-\delta_g} (1 - \rho)^{\beta_{Eg}}\end{aligned}$$

where κ_q is the flavour-q contribution to the nucleon anomalous magnetic moment ($\kappa_u = 1.67$, $\kappa_d = -2.03$)

$$\begin{aligned}\beta_{val}^u &= 4, \quad \beta_{val}^d = 5.6, \quad \alpha'_{eval} = \alpha'_{hval}, \quad b_{eval} = 0 \\ \beta_{Es} &= 7, \quad \beta_{Eg} = 6, \quad b_{eg} = b_{es} = 0.9 b_{hg}\end{aligned}$$



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The Goloskokov–Kroll model of the GPDs

Parametrization of the GPD \tilde{H}

$$\tilde{H}_{val}^q(\rho, \xi = 0, t = 0) = n_q A_q \rho^{-\alpha_{\tilde{h}q}} (1 - \rho)^3 \sum_{j=0}^2 \tilde{c}_{qj} \rho^j$$

(\tilde{H}_{sea}^q , \tilde{H}_g^q are neglected) where $n_u = 0.926 \pm 0.014$, $n_d = 0.341 \pm 0.018$.
 A_q is the normalization factor:

$$A_q^{-1} = B(1 - \alpha_{\tilde{h}q}, 4) \left(\tilde{c}_{q0} + \tilde{c}_{q1} \frac{1 - \alpha_{\tilde{h}q}}{5 - \alpha_{\tilde{h}q}} + \tilde{c}_{q2} \frac{(2 - \alpha_{\tilde{h}q})(1 - \alpha_{\tilde{h}q})}{(6 - \alpha_{\tilde{h}q})(5 - \alpha_{\tilde{h}q})} \right)$$

	u_{val}	d_{val}
$\alpha_{\tilde{h}}$	0.48	0.48
$b_{\tilde{h}}$	0	0
\tilde{c}_0	$0.170 + 0.03L$	$-0.320 - 0.040L$
\tilde{c}_1	$1.340 - 0.02L$	$-1.427 - 0.176L$
\tilde{c}_2	$0.120 - 0.40L$	$0.692 - 0.068L$

Parametrization of the GPD \tilde{E}

$$\tilde{E}_{val}^q(\rho, \xi = t = 0) = N_{\tilde{e}}^q \rho^{\alpha_{\tilde{e}}} (1 - \rho)^5$$

$$\begin{array}{cccc} \alpha_{\tilde{e}} & b_{\tilde{e}} & N_{\tilde{e}}^u & N_{\tilde{e}}^d \\ 0.48 & 0.9 \text{ GeV}^{-1} & 14.0 & 4 \end{array}$$



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Parameters

Definition of t :

$$t = (p_2 - p_1)^2 = -\frac{4M^2\xi^2}{1-\xi^2} - \Delta_t^2 \frac{1+\xi}{1-\xi}$$

The following calculations are done for $(-t)_{min} = t|_{\Delta_\perp=0}$

Integration:

Integration is taken by using trapezoidal rule.

$$2.10 \text{ GeV}^2 \leq M_{\gamma\gamma}^2 \leq 9.47 \text{ GeV}^2$$

$$(-u')_{min} \leq (-u') \leq (-u')_{maxMax}$$

$$(-u')_{min} = 1 \text{ GeV}^2$$

$$(-u')_{maxMax} = (-t) + M_{\gamma\gamma}^2 - (-t')_{min}$$

$$(-t')_{min} = 1 \text{ GeV}^2$$

The domain of integration is taken in analogy with the paper: *R. Boussarie, B. Pire, L. Szymanowski, S. Wallon "Exclusive photoproduction of a $\gamma\rho$ pair with a large invariant mass"* arXiv:1609.03830v1.



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