

High-energy resummation in two heavy-quark pairs production in photon-photon collisions

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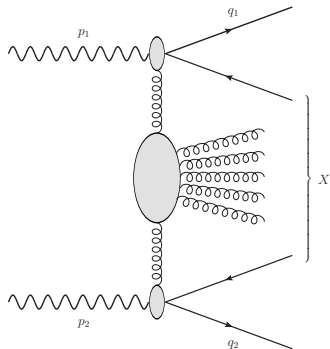
BFKL approach

- ▶ **BFKL resummation** – the basis of our understanding of semihard processes, characterized by a clear hierarchy of scales, $s \gg Q^2 \gg \Lambda_{\text{QCD}}^2$.
- ▶ [1975] **Fadin, Kuraev, Lipatov** - LLA resummation ($\sim (\alpha_s \ln(s))^n$) in gauge theories with massive gauge bosons.
- ▶ [1978] **Balitsky, Lipatov** - LLA resummation in QCD. Infrared safe predictions for color singlet (Pomeron channel).
Example: total inclusive cross section of $\gamma\gamma \rightarrow Q\bar{Q} + X + Q\bar{Q}$.
- ▶ [1998] **Fadin, Lipatov** - NLA resummation ($\sim \alpha_s(\alpha_s \ln(s))^n$) in QCD
- ▶ In most cases - hard scale does not guarantee the dominance of small distances. BFKL is used together with collinear factorization...
Also I just mention here related with BFKL the dipole approach and its modern developments related with saturation problem.
- ▶ **my topic**: - processes where BFKL can be directly used and confronted with experiment.
In particular – heavy quark photoproduction $\gamma\gamma \rightarrow Q\bar{Q} + X + Q\bar{Q}$

BFKL phenomenology:

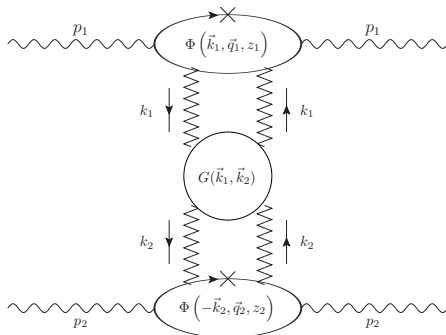
- ▶ Total cross section of $\gamma^*(Q_1)\gamma^*(Q_2) \rightarrow X$ (NLA BFKL) – e^+e^- experiments at LEP2.
- ▶ Mueller-Navelet jets production $pp \rightarrow Jet + X + Jet$ (NLA BFKL) – CMS experiment at LHC
- ▶ Inclusive di-hadron production $pp \rightarrow h_1 + X + h_2$ (NLA BFKL) – proposal for LHC: [2016-2017] our group.
- ▶ More jets separated by large rapidity intervals like $pp \rightarrow Jet + X + Jet + X + Jet$ – proposal for LHC [2016-2017] Celiberto, Chachamis, Sabio Vera ...
- ▶ Why heavy quark photoproduction $\gamma\gamma \rightarrow Q\bar{Q} + X + Q\bar{Q}$?
 1. It is an option for heavy ions UPC experiments at LHC
 2. It is exiting to return back to Balitsky, Lipatov [1978] paper, from which the whole BFKL business was started ...
 3. In order to confront with experiment one needs to consider less inclusive observables

Heavy quark photoproduction



in the case when a heavy quark with transverse momentum q_1 (q_2) from the upper (lower) vertex is tagged (detected).

BFKL cross section



– convolution of the BFKL Green's function and two impact factors. We need impact factors for photoproduction of heavy quark pair when momentum of a quark (an antiquark) is fixed (tagged).

Tagged impact factor

is build from the well known differential amplitude for the pair photoproduction

$$d\phi = \frac{\alpha\alpha_s e_Q^2}{\pi} \left[m^2 R^2 + \vec{P}^2 (z^2 + \bar{z}^2) \right] d^2q dz,$$

where R and \vec{P} read

$$R = \frac{1}{m^2 + \vec{q}^2} - \frac{1}{m^2 + (\vec{q} - \vec{k})^2}, \quad \vec{P} = \frac{\vec{q}}{m^2 + \vec{q}^2} + \frac{\vec{k} - \vec{q}}{m^2 + (\vec{q} - \vec{k})^2}.$$

where \vec{q} and z are transverse momentum and longitudinal fraction of tagged quark, and \vec{k} – transverse momentum of the Reggeized gluon.

To get tagged quark IF – to make square of this amplitude and to project onto the eigenfunction of LLA BFKL equation, $\sim (k^2)^{i\nu-3/2} e^{in\vartheta}$. To get its so called (n, ν) -representation.

Tagged impact factor

$$\begin{aligned}v_{R^2} &\equiv \int \frac{d^2k}{\pi\sqrt{2}} (k^2)^{i\nu-3/2} e^{in\vartheta} R^2 \\&= \frac{1}{\sqrt{2}} \frac{\Gamma\left(\frac{1}{2} + \frac{n}{2} - i\nu\right) \Gamma\left(\frac{1}{2} + \frac{n}{2} + i\nu\right) (\vec{q}^2)^{\frac{n}{2}} e^{in\varphi} \left(\frac{1}{2} + \frac{n}{2} - i\nu\right)}{\Gamma(n+1) (m^2 + \vec{q}^2)^{\frac{5}{2} + \frac{n}{2} - i\nu} \left(\frac{n}{2} + i\nu - \frac{1}{2}\right)} \\&\times \left[\left(\frac{3}{2} + \frac{n}{2} - i\nu\right) {}_2F_1\left(\frac{n}{2} - \frac{1}{2} + i\nu, \frac{5}{2} + \frac{n}{2} - i\nu, 1+n, \zeta\right) \right. \\&\quad \left. - 2 {}_2F_1\left(\frac{n}{2} - \frac{1}{2} + i\nu, \frac{3}{2} + \frac{n}{2} - i\nu, 1+n, \zeta\right) \right] \\&\equiv e^{in\varphi} c_{R^2}(n, \nu, \vec{q}^2)\end{aligned}$$

and similar equation for the projection of \vec{P}^2 structure

Photoproduction differential cross section

$$\frac{d\sigma}{dy_1 dy_2 d|\vec{q}_1| d|\vec{q}_2| d\phi_1 d\phi_2} = \frac{1}{(2\pi)^2} \left[C_0 + 2 \sum_{n=1}^{\infty} \cos(n\varphi) C_n \right],$$

where $\varphi = \varphi_1 - \varphi_2 - \pi$, while C_0 gives the cross section averaged over the azimuthal angles $\varphi_{1,2}$ of the produced quarks and the other coefficients C_n determine the distribution of the relative azimuthal angle between the two quarks.

($q_{1,2} \equiv |\vec{q}_{1,2}|$):

$$C_n = \frac{q_1 q_2 \sqrt{m_1^2 + q_1^2} \sqrt{m_2^2 + q_2^2}}{W^2} e^{\Delta Y}$$

$$\times \int d\nu \left(\frac{W^2}{s_0} \right)^{\bar{\alpha}_s(\mu_R) \chi(n, \nu) + \bar{\alpha}_s^2(\mu_R) \left(\bar{\chi}(n, \nu) + \frac{\beta_0}{8N_c} \chi(n, \nu) \left(-\chi(n, \nu) + \frac{10}{3} + 2 \ln \frac{\mu_R^2}{\sqrt{s_1 s_2}} \right) \right)}$$

$$\times \alpha_s^2(\mu_R) c_1(n, \nu, \vec{q}_1^2, z_1) c_2(n, \nu, \vec{q}_2^2, z_2)$$

$$\times \left\{ 1 + \bar{\alpha}_s(\mu_R) \left(\frac{\bar{c}_1^{(1)}}{c_1} + \frac{\bar{c}_2^{(1)}}{c_2} \right) + \bar{\alpha}_s(\mu_R) \frac{\beta_0}{2N_c} \left(\frac{5}{3} + \ln \frac{\mu_R^2}{s_1 s_2} + f(\nu) \right) \right.$$

$$\left. + \bar{\alpha}_s^2(\mu_R) \ln \left(\frac{W^2}{s_0} \right) \frac{\beta_0}{4N_c} \chi(n, \nu) f(\nu) \right\},$$

convolution with the WW photon spectrum:

$$d\sigma_{e^+e^-} = dn_1 dn_2 d\sigma_{\gamma\gamma},$$

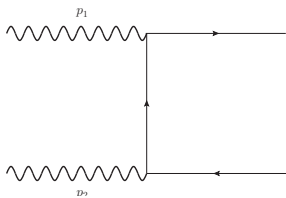
with

$$dn = \frac{\alpha}{\pi} \frac{dx}{x} \left[\left(1 - x + \frac{x^2}{2} \right) \ln \left(\frac{E_e^2 \theta_0^2 (1-x)^2 + m_e^2 x^2}{m_e^2 x^2} \right) - (1-x) \right],$$

θ_0 - is antitag electron angle parameter.

$$\begin{aligned} \frac{d\sigma_{e^+e^-}}{d(\Delta Y)} &= \int dq_1 \int dq_2 \int_{-y_{\max}^{(1)}}^{y_{\max}^{(1)}} dy_1 \int_{-y_{\max}^{(2)}}^{y_{\max}^{(2)}} dy_2 \delta(y_1 - y_2 - \Delta Y) \\ &\times \int_e^1 \int_{e^{-(y_{\max}^{(1)} - y_1)}}^{(y_{\max}^{(1)} - y_1)} \frac{dn_1}{dx_1} dx_1 \int_e^1 \int_{e^{-(y_{\max}^{(2)} + y_2)}}^{(y_{\max}^{(2)} + y_2)} \frac{dn_2}{dx_2} dx_2 d\sigma_{\gamma\gamma}, \end{aligned}$$

The "box" $Q\bar{Q}$ cross section



$$\frac{d\sigma_{ee}}{d(\Delta Y)} = \int_0^{\frac{s_{ee}}{2(1+\cosh(\Delta Y))} - m^2} dq^2 \frac{2\pi\alpha^2 e_q^4 N_c}{(m^2 + q^2)^2 (1 + \cosh(\Delta Y))^2} \left[\frac{\cosh(\Delta Y)}{2} + \frac{m^2}{m^2 + q^2} - \left(\frac{m^2}{m^2 + q^2} \right)^2 \right] \times \left(\frac{\alpha}{\pi} \right)^2 \left[f(y) \left(\ln \left(\frac{\Lambda^2}{m_e^2 y} \right) - 1 \right)^2 - \frac{1}{3} \left(\ln \frac{1}{y} \right)^3 \right],$$

where

$$y = \frac{w^2}{s_{ee}} = \frac{2(1 + \cosh(\Delta Y))(m^2 + q^2)}{s_{ee}},$$

with

$$f(y) = \left(1 + \frac{y}{2}\right)^2 \ln \frac{1}{y} - \frac{1}{2}(1 - y)(3 + y)$$

and $\Lambda \simeq m^2$.

Box vs BFKL

ΔY -dependence of the φ -averaged cross section C_0 [pb] for $q_{\min} = 0$ GeV.

$\sqrt{s} = 200$ GeV.

ΔY	Box $q\bar{q}$	NLA, $C = 1/2$	NLA, $C = 1$	NLA, $C = 2$
1.5	98.26	2.120(13)	1.4046(91)	1.2861(93)
2.5	42.73	2.197(11)	1.1976(71)	1.067(7)
3.5	14.077	2.315(12)	0.9986(54)	0.8296(45)
4.5	3.9497	2.3015(23)	0.7763(39)	0.6116(32)
5.5	0.9862	2.12(1)	0.5411(27)	0.3922(19)

$\sqrt{s} = 3$ TeV.

ΔY	Box $q\bar{q}$	NLA, $C = 1/2$	NLAC = 1	NLAC = 2
1.5	280.98	12.45(11)	7.292(72)	6.521(73)
3.5	48.93	23.07(14)	8.153(62)	6.798(59)
5.5	4.9819	47.53(23)	9.479(67)	6.903(45)
7.5	0.4318	94.54(44)	10.243(56)	6.435(33)
9.5	0.0323	158.38(76)	9.092(45)	4.858(24)
10.5	0.0081	180.4(9)	7.497(37)	3.651(18)

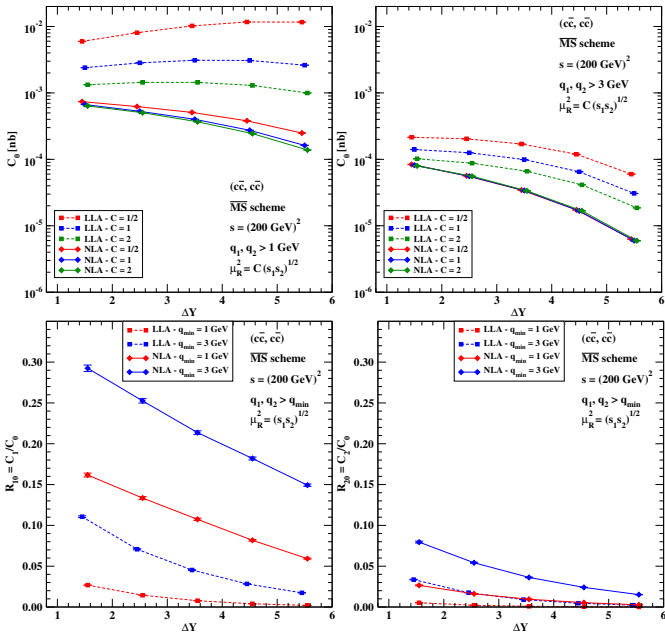


Figure: ΔY -dependence of C_0 , R_{10} , and R_{20} for $q_{\min} = 1, 3 \text{ GeV}$, $\sqrt{s} = 200 \text{ GeV}$, and for different values of $C = \mu_R^2 / \sqrt{s_1 s_2}$, with $s_{1,2} = m_{1,2}^2 + q_{1,2}^2$.

Future e^+e^- collider

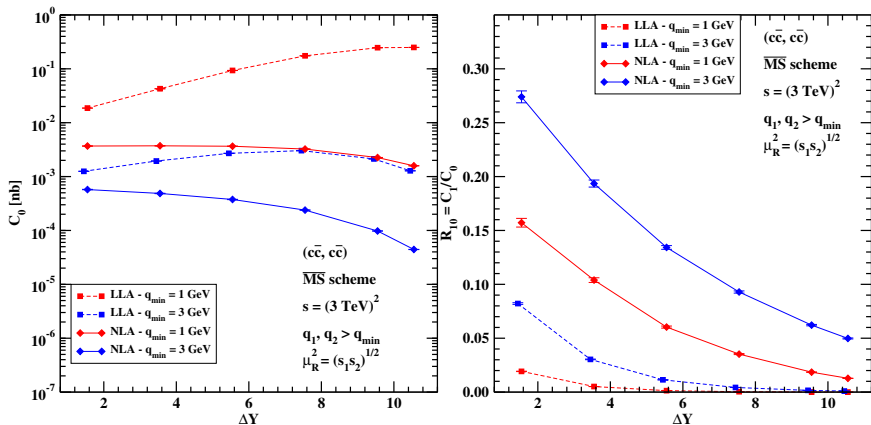


Figure: ΔY -dependence of C_0 and R_{10} for $q_{\min} = 1, 3 \text{ GeV}$, $\sqrt{s} = 3 \text{ TeV}$, and for $\mu_R^2 = \sqrt{s_1 s_2}$, with $s_{1,2} = m_{1,2}^2 + q_{1,2}^2$.

Heavy ions UPC at LHC

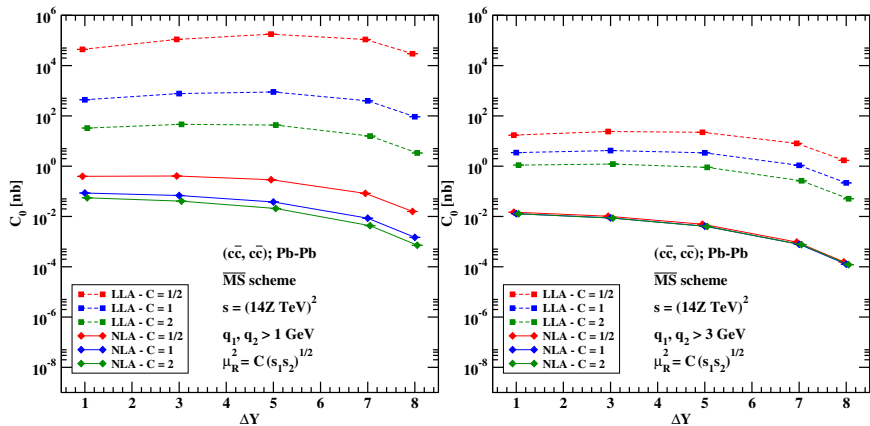


Figure: ΔY -dependence of C_0 for $q_{\min} = 1, 3 \text{ GeV}$, $\sqrt{s} = 3 \text{ TeV}$, and for $\mu_R^2 = \sqrt{s_1 s_2}$, with $s_{1,2} = m_{1,2}^2 + q_{1,2}^2$.

Summary and outlook

- ▶ We performed analysis of inclusive heavy quark photoproduction process where two heavy quarks are detected separated by large rapidity interval.
- ▶ This process extends the list of semihard processes by which strong interactions in the high-energy limit, and in particular the BFKL resummation procedure, can be probed at the LHC and in future linear colliders.

possible developments:

- ▶ NLA impact factors – Complete NLA predictions
- ▶ Treatment of heavy quark fragmentation.
- ▶ From photoproduction to the processes initiated by the gluons. It opens the way to study similar process in proton-proton collision at LHC:
 $pp \rightarrow Q\bar{Q} + X + Q\bar{Q}$