Diffractive production of quark-antiquark pairs

Antoni Szczurek

Institute of Nuclear Physics (PAN), Cracow, Poland

Rzeszow University, Rzeszow, Poland

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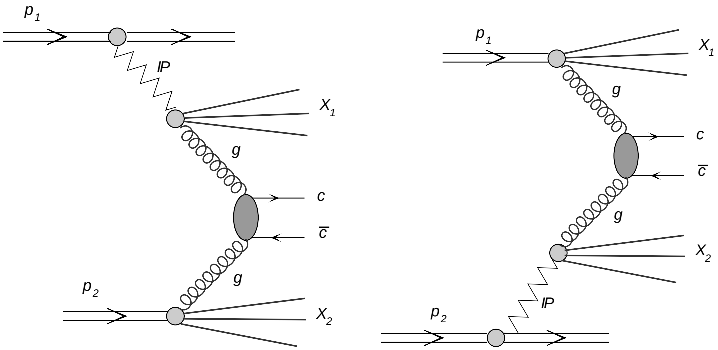
Contents

- Ingelman-Schlein model
- Results
- Diffractive amplitude for $gp \to Q\bar{Q}p$
  - Impact parameter space
  - Momentum space
- Hadron level cross section
- First results
  - Differential distributions
  - $b\bar{b}$ to $c\bar{c}$ ratios
- Photon-induced processes
- Summary and conclusions

Ingelman-Schlein approach



Luszczak, Maciula, Szczurek, Phys. Rev. **D84** (2011) 4018

Ingelman-Schlein approach

In this approach (Ingelman-Schlein model) one assumes that the Pomeron has a well defined partonic structure, and that the hard process takes place in a Pomeron--proton or proton--Pomeron (single diffraction) or Pomeron--Pomeron (central diffraction) processes.

$$\frac{d\sigma_{SD}}{dy_1 dy_2 dp_t^2} = K \frac{|M|^2}{16\pi^2 \hat{s}^2} \Big[\Big(x_1 g^D(x_1, \mu^2)\, x_2 g(x_2, \mu^2) \Big)$$

$$+ \Big(x_1 g^D(x_1, \mu^2)\, x_2 g(x_2, \mu^2) \Big) \Big],$$

$$\frac{d\sigma_{CD}}{dy_1 dy_2 dp_t^2} = K \frac{|M|^2}{16\pi^2 \hat{s}^2} \Big[\Big(x_1 g^D(x_1, \mu^2)\, x_2 g^D(x_2, \mu^2) \Big)$$

$$+ \Big(x_1 g^D(x_1, \mu^2)\, x_2 g^D(x_2, \mu^2) \Big) \Big]$$

Ingelman-Schlein approach

The 'diffractive' quark distribution of flavour f can be obtained by a convolution of the flux of Pomerons $f_{\mathbf{P}}(x_{\mathbf{P}})$ and the parton distribution in the Pomeron $g_{\mathbf{P}}(\beta, \mu^2)$:

$$g^D(x, \mu^2) = \int dx_{\mathbf{P}} d\beta\, \delta(x - x_{\mathbf{P}}\beta) g_{\mathbf{P}}(\beta, \mu^2)\, f_{\mathbf{P}}(x_{\mathbf{P}}) = \int_x^1 \frac{dx_{\mathbf{P}}}{x_{\mathbf{P}}} f_{\mathbf{P}}(x_{\mathbf{P}}) g_{\mathbf{P}}(\frac{x}{x_{\mathbf{P}}}, \mu^2)\,.$$

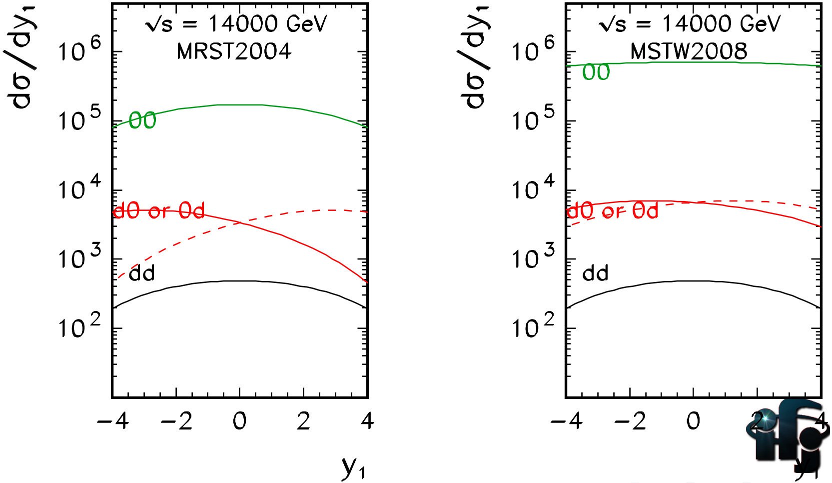
The flux of Pomerons $f_{\mathbf{P}}(x_{\mathbf{P}})$:

$$f_{\mathbf{P}}(x_{\mathbf{P}}) = \int_{t_{min}}^{t_{max}} dt\, f(x_{\mathbf{P}}, t)\,,$$

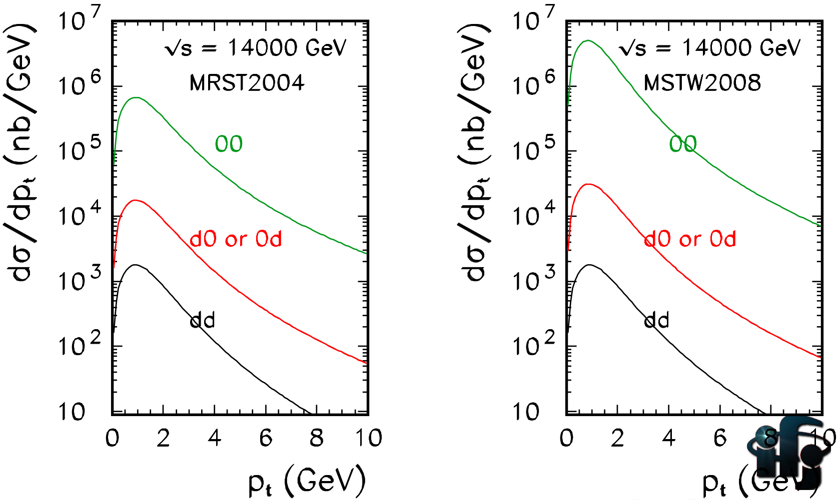
with t_{min}, t_{max} being kinematic boundaries.

Both pomeron flux factors $f_{\mathbf{P}}(x_{\mathbf{P}}, t)$ as well as gluon distributions in the pomeron were taken from the H1 collaboration analysis of diffractive structure function at HERA.

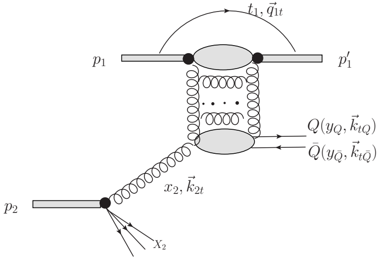
Ingelman-Schlein, result

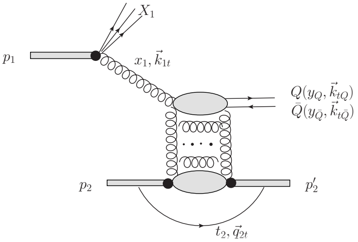


Ingelman-Schlein, results



Gluon dissociation mechanism





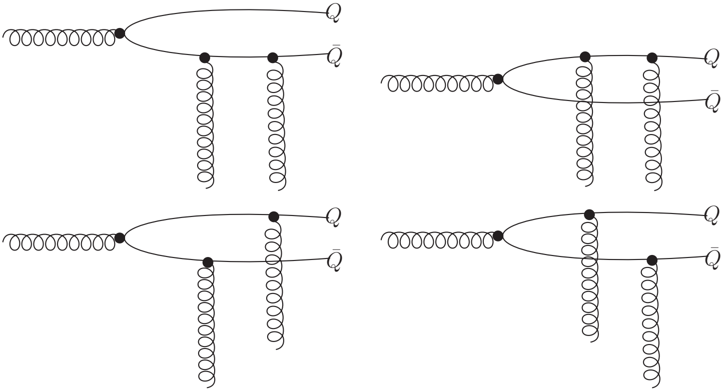
Luszczak, Schäfer, Szczurek, a paper in preparation

special final state topology

proton-gap-$Q\bar{Q}$ – X or X-$Q\bar{Q}$-gap-proton

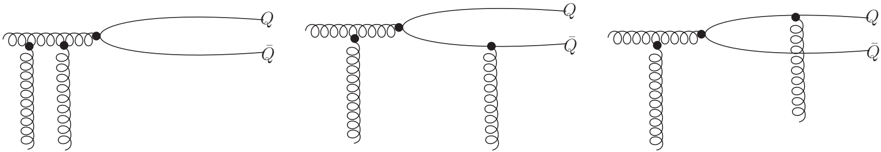
$Q\bar{Q}$ next to gap

Diagrams contributing to gluon dissociation



as for $\gamma \to Q\bar{Q}$

New diagrams for gluon dissociation



not present for $\gamma \to Q\bar{Q}$

the first diagram partially cancels with the first two standard diagrams

Impact parameter space

The amplitude for the diffractive process $gN \to Q\bar{Q}N$ can be written in impact parameter-space, where the impact parameters of gluon, quark and antiquark are $\boldsymbol{b}, \boldsymbol{b}_+, \boldsymbol{b}_-$, respectively:

$$\mathcal{A}_D(g^a_{\lambda_g} N \to Q_{\lambda} \bar{Q}_{\bar{\lambda}} N) = \int [\mathcal{D}\boldsymbol{b}] \exp[-i\boldsymbol{p}_+\boldsymbol{b}_+ - i\boldsymbol{p}_-\boldsymbol{b}_-]\langle N|\mathcal{M}^a(\boldsymbol{b}_+, \boldsymbol{b}_-, \boldsymbol{b})|N\rangle \psi^{\lambda_g}_{\lambda,\bar{\lambda}}(z,$$

The integration over impact parameters

$$[\mathcal{D}\boldsymbol{b}] = d^2\boldsymbol{b}_+ d^2\boldsymbol{b}_- d^2\boldsymbol{b}\, \delta^{(2)}(\boldsymbol{b} - z\boldsymbol{b}_+ - (1-z)\boldsymbol{b}_-)\,, \qquad (2)$$

ensures the conservation of orbital angular momentum. Quark and antiquark share the lightcone-momentum of the incoming gluon $z, 1-z$, and have the transverse momenta $\boldsymbol{p}_+, \boldsymbol{p}_-$. The transition $g_{\lambda_g} \to Q_{\lambda}\bar{Q}_{\bar{\lambda}}$ is described by the lightcone wave-function $\psi^{\lambda_g}_{\lambda,\bar{\lambda}}$. The interaction of partons with the target is described by the operator

$$\mathcal{M}^a(\boldsymbol{b}_+, \boldsymbol{b}_-, \boldsymbol{b}) = \Big[S(\boldsymbol{b}_+)t^a S^\dagger(\boldsymbol{b}_-) - S(\boldsymbol{b})t^a S^\dagger(\boldsymbol{b})\Big]\,. \qquad (3)$$

Impact parameter space

Here the quark-proton S-matrix $S(\boldsymbol{b}_+)$ is written in terms of the gluon-exchange eikonal $\hat{\chi} = \chi^a t^a$, as

$$S(\boldsymbol{b}_+) = 1 + i\hat{\chi}(\boldsymbol{b}_+) - \frac{1}{2}\hat{\chi}^2(\boldsymbol{b}_+)\,, \tag{4}$$

the antiquark interacts with the complex-conjugate S-matrix $S^\dagger(\boldsymbol{b}_-)$, and a gluon interacts in the same fashion as a pointlike color-octet $Q\bar{Q}$ pair and its scattering is described by $S(\boldsymbol{b})t^a S^\dagger(\boldsymbol{b})$.

As we are interested in a diffractive process, with no color-transfer to the target, only the terms of quadratic order in the eikonal will contribute. They correspond to the coupling of two gluons in the color-singlet state to the nucleon:

$$\langle N|\chi^a(\boldsymbol{b}_+)\chi^b(\boldsymbol{b}_-)|N\rangle = \delta^{ab}\,\chi^{(2)}(\boldsymbol{b}_+,\boldsymbol{b}_-)\,, \tag{5}$$

which we parametrize as

$$C_F \cdot \chi^{(2)}(\boldsymbol{b}_+,\boldsymbol{b}_-) = \int \frac{d^2\boldsymbol{q}}{(2\pi)^2}\frac{d^2\kappa}{(2\pi)^2}\, f(x,\frac{\boldsymbol{q}}{2}+\kappa,\frac{\boldsymbol{q}}{2}-\kappa)\,\exp[i\frac{\boldsymbol{q}}{2}(\boldsymbol{b}_+ + \boldsymbol{b}_-)]\,\exp[i\kappa(\boldsymbol{b}$$

Impact parameter space

$$f(x,\kappa_1,\kappa_2) = \frac{(2\pi)^3}{N_c} \cdot \frac{\alpha_S \mathcal{F}(x,\kappa_1,\kappa_2)}{\kappa_1^2 \kappa_2^2}\,, \tag{7}$$

where $\mathcal{F}$ UGDF is related to the familiar integrated gluon structure function as

$$\mathcal{F}(x,\kappa,-\kappa) \approx \frac{\partial[xg(x,\kappa^2)]}{\partial \log(\kappa^2)}\,. \tag{8}$$

The full f is often parametrized as

$$f(x,\frac{\boldsymbol{q}}{2}+\kappa,\frac{\boldsymbol{q}}{2}-\kappa) = \frac{(2\pi)^3}{N_c}\frac{\alpha_S}{\kappa^4}\frac{\partial[xg(x,\kappa^2)]}{\partial \log(\kappa^2)}\;\exp[-\frac{1}{2}B_D\boldsymbol{q}^2]\,, \tag{9}$$

where the diffractive slope B_D is a nonperturbative quantity that takes care of the size of the target and in accord with Regge-phenomenology $B_D = B_0 + \alpha'_{\mathbf{P}}\log(x_0/x)$.

Impact parameter space

We then obtain:

$$\langle N|\mathcal{M}^a(\boldsymbol{b}_+,\boldsymbol{b}_-,\boldsymbol{b})|N\rangle = t^a\Big\{\frac{1}{2N_cC_F}\,\Gamma^{(2)}(\boldsymbol{b}_+,\boldsymbol{b}_-) - \frac{N_c}{2C_F}\,\bar{\Gamma}^{(2)}(\boldsymbol{b}_+,\boldsymbol{b}_-)\Big\}. \quad (10)$$

Here

$$\begin{aligned}
\Gamma^{(2)}(\boldsymbol{b}_+,\boldsymbol{b}_-) &= \frac{C_F}{2}\cdot\Big[\chi^{(2)}(\boldsymbol{b}_+,\boldsymbol{b}_+) + \chi^{(2)}(\boldsymbol{b}_-,\boldsymbol{b}_-) - \chi^{(2)}(\boldsymbol{b}_+,\boldsymbol{b}_-) - \chi^{(2)}(\boldsymbol{b}_-,\boldsymbol{b}_+)\\
\bar{\Gamma}^{(2)}(\boldsymbol{b}_+,\boldsymbol{b}_-) &= \frac{C_F}{2}\cdot\Big[\chi^{(2)}(\boldsymbol{b}_+,\boldsymbol{b}_+) + \chi^{(2)}(\boldsymbol{b}_-,\boldsymbol{b}_-) - 2\chi^{(2)}(\boldsymbol{b},\boldsymbol{b})\Big]. \qquad (
\end{aligned}$$

Here the profile function $\Gamma^{(2)}(\boldsymbol{b}_+,\boldsymbol{b}_-)$ is related to the familar color-dipole cross section through the relation

$$\sigma(\boldsymbol{r}) = 2\int d^2\,\Gamma^{(2)}(+\frac{\boldsymbol{r}}{2},-\frac{\boldsymbol{r}}{2})\,. \quad (12)$$

Impact parameter space

We can write the relevant profile functions in terms of the off-diagonal gluon density as:

$$\begin{aligned}
\Gamma^{(2)}(\boldsymbol{b}_+, \boldsymbol{b}_-) &= \int \frac{d^2\boldsymbol{q}}{(2\pi)^2} \frac{d^2\kappa}{(2\pi)^2} f(x, \frac{\boldsymbol{q}}{2} + \kappa, \frac{\boldsymbol{q}}{2} - \kappa) \exp[i\frac{\boldsymbol{q}}{2}(\boldsymbol{b}_+ + \boldsymbol{b}_-)] \;, \\
&\Big\{ \exp[i\frac{\boldsymbol{q}}{2}(\boldsymbol{b}_+ - \boldsymbol{b}_-)] + \exp[-i\frac{\boldsymbol{q}}{2}(\boldsymbol{b}_+ - \boldsymbol{b}_-)] - \exp[i\kappa(\boldsymbol{b}_+ - \boldsymbol{b}_-)] - \exp[-i\kappa(\boldsymbol{b}_+ - \boldsymbol{b}_-)] \Big\} \\
\bar{\Gamma}^{(2)}(\boldsymbol{b}_+, \boldsymbol{b}_-) &= \int \frac{d^2\boldsymbol{q}}{(2\pi)^2} \frac{d^2\kappa}{(2\pi)^2} f(x, \frac{\boldsymbol{q}}{2} + \kappa, \frac{\boldsymbol{q}}{2} - \kappa) \Big[\exp[i\boldsymbol{q}\boldsymbol{b}_+] + \exp[i\boldsymbol{q}\boldsymbol{b}_-] - 2\exp[i\boldsymbol{q}\boldsymbol{b}] \Big] .
\end{aligned} \tag{13}$$

We introduce the usual parametrization of transverse momenta: the decorrelation momentum of jets (or momentum transfer to the proton) $\boldsymbol{\Delta} = \boldsymbol{p}_+ + \boldsymbol{p}_-$ and the light-cone relative transverse momentum $\boldsymbol{k} = (1-z)\boldsymbol{p}_+ - z\boldsymbol{p}_-$, which is conjugate to the dipole size $\boldsymbol{r} = \boldsymbol{b}_+ - \boldsymbol{b}_-$.

Impact parameter space

We then notice, that

$$[\mathcal{D}\boldsymbol{b}]\exp[-i\boldsymbol{k}(\boldsymbol{b}_+ - \boldsymbol{b}_-) - i\boldsymbol{\Delta}(z\boldsymbol{b}_+ + (1-z)\boldsymbol{b}_-)] = d^2\boldsymbol{b}d^2\boldsymbol{r}\,\exp[-i\boldsymbol{\Delta}\boldsymbol{b}]\,\exp[-i\boldsymbol{k}\boldsymbol{r}]\,, \tag{14}$$

so that

$$\begin{aligned}\mathcal{A}_D(g^a N \to Q\bar{Q}N) &= \int d^2\boldsymbol{b}d^2\boldsymbol{r}\,\exp[-i\boldsymbol{\Delta}\boldsymbol{b}]\exp[-i\boldsymbol{k}\boldsymbol{r}]\,\psi^{\lambda g}_{\lambda,\bar{\lambda}}(z,\boldsymbol{r})\\ &\langle N|\mathcal{M}^a(\boldsymbol{b}+(1-z)\boldsymbol{r},\boldsymbol{b}-z\boldsymbol{r},\boldsymbol{b})|N\rangle\\ &= t^a \int d^2\boldsymbol{b}d^2\boldsymbol{r}\,\exp[-i\boldsymbol{\Delta}\boldsymbol{b}]\exp[-i\boldsymbol{k}\boldsymbol{r}]\,\psi^{\lambda g}_{\lambda,\bar{\lambda}}(z,\boldsymbol{r})\\ &\Big\{\frac{1}{2N_cC_F}\,\Gamma^{(2)}(\boldsymbol{b}+(1-z)\boldsymbol{r},\boldsymbol{b}-z\boldsymbol{r}) - \frac{N_c}{2C_F}\,\bar{\Gamma}^{(2)}(\boldsymbol{b}+(1-z)\boldsymbol{r},\boldsymbol{b}-z\boldsymbol{r})\Big\}.\end{aligned}$$

The term $\propto \bar{\Gamma}^{(2)}$ vanishes in the forward direction $\boldsymbol{\Delta} = 0$.

Momentum space

For the forward amplitude we can then easily derive:

$$\begin{aligned} \mathcal{A}_D(g^a N \to Q\bar{Q}N)|_{\boldsymbol{\Delta}=0} &= \frac{t^a}{2N_c C_F}\int \frac{d^2\kappa}{(2\pi)^2} f(x,\kappa,-\kappa) \\ &\times\Big[2\psi^{\lambda_g}_{\lambda,\bar{\lambda}}(z,\boldsymbol{k}) - \psi^{\lambda_g}_{\lambda,\bar{\lambda}}(z,\boldsymbol{k}+\kappa) - \psi^{\lambda_g}_{\lambda,\bar{\lambda}}(z,\boldsymbol{k}-\kappa)\Big] \\ &= \frac{t^a}{2N_c C_F}\frac{4\pi}{N_c} \\ &\int \frac{d^2\kappa}{\kappa^4}\alpha_S \mathcal{F}(x,\kappa,-\kappa)\Big[\psi^{\lambda_g}_{\lambda,\bar{\lambda}}(z,\boldsymbol{k}) - \psi^{\lambda_g}_{\lambda,\bar{\lambda}}(z,\boldsymbol{k}+\kappa)\Big] \end{aligned} \tag{15}$$

Our amplitude can now be expressed in terms of the integrals:

$$\left.\begin{matrix}\boldsymbol{\Phi}_1 \\ \Phi_0\end{matrix}\right\} = \int \frac{d^2\kappa}{\pi\kappa^4}\alpha_S\mathcal{F}(x,\kappa,-\kappa)\begin{cases}\dfrac{\boldsymbol{k}}{\boldsymbol{k}^2+m_Q^2} - \dfrac{\boldsymbol{k}+\kappa}{(\boldsymbol{k}+\kappa)^2+m_Q^2} \\ \dfrac{1}{\boldsymbol{k}^2+m_Q^2} - \dfrac{1}{(\boldsymbol{k}+\kappa)^2+m_Q^2}\end{cases} . \tag{16}$$

Momentum space

Let us write it out explicitly for the different helicities:

$$\mathcal{A}_D(g^a_{\lambda_g} N \to Q_\lambda \bar{Q}_{\bar\lambda} N)|_{\mathbf{\Delta}=0} = \frac{t^a}{2N_c C_F}\frac{4\pi^2}{N_c}\sqrt{\alpha_S} \Big\{ 2\delta_{\lambda - \bar\lambda}\Big[z\delta_{\lambda_g \lambda} - (1-z)\delta_{\lambda_g \bar\lambda}\Big](\mathbf{\Phi}_1 \cdot \boldsymbol{e}(\lambda_g)) - \delta_{\lambda\bar\lambda}\delta_{\lambda_g \lambda}\sqrt{2} m_Q \Phi_0 \Big\} \tag{17}$$

Then, if we put everything together, one gets for the differential parton-level cross section

$$16\pi \frac{d\sigma(gN \to Q\bar{Q}N;\hat{s})}{d\mathbf{\Delta}^2}\Big|_{\mathbf{\Delta}^2=0} = \frac{1}{2\cdot(N_c^2-1)} \cdot \sum_{\lambda_g,\lambda,\bar\lambda,a} \Big|\mathcal{A}_D(g^a_{\lambda_g} N \to Q_\lambda \bar{Q}_{\bar\lambda} N)\Big|^2 \frac{dz d^2\boldsymbol{k}}{(2\pi)^2}$$

Momentum space

Final multi-dimensional cross section reads:

$$\frac{d\sigma(gN \to Q\bar{Q}N;\hat{s})}{dz d^2\mathbf{k} d\mathbf{\Delta}^2}\Big|_{\mathbf{\Delta}^2=0} = \frac{\pi/4}{N_c^2(N_c^2-1)^2}\,\alpha_S\Big\{[z^2+(1-z)^2]\mathbf{\Phi}_1^2 + m_Q^2\Phi_0^2\Big\}. \quad (19)$$

Forward direction only

t-dependence assumed to be exponential

Hadronic cross section

The cross section for single diffractive production of $Q\bar{Q}$ (diagram b)) can be written as a convolution of the elementary cross section for the $gp \to Q\bar{Q}X$ and the gluon distribution in the proton as:

$$\frac{d\sigma_{pp\to Q\bar{Q}X}}{dzd^2k_t dt_2} = \int_0^1 dx_1 g_1(x_1,\mu_F^2) \frac{d\sigma_{gp\to Q\bar{Q}X}}{dzd^2k_t dt_2} \ . \quad (20)$$

The cross section for the diagram a) can be obtained by trivial replacement of x_1 by x_2 and t_2 by t_1.

$g_1(x_1,\mu_F^2)$ collinear gluon distribution (flux of gluons).

$$x_1 = \frac{m_{1t}}{\sqrt{s}}\exp(+y_1) + \frac{m_{2t}}{\sqrt{s}}\exp(+y_2) \ ,$$
$$x_2 = \frac{m_{1t}}{\sqrt{s}}\exp(-y_1) + \frac{m_{2t}}{\sqrt{s}}\exp(-y_2) \ . \quad (21)$$

Rapidities - kinematics

$$y_Q = \frac{1}{2}\log\left(\frac{p_Q^+}{p_Q^-}\right), \; y_{\bar{Q}} = \frac{1}{2}\log\left(\frac{p_{\bar{Q}}^+}{p_{\bar{Q}}^-}\right) \tag{22}$$

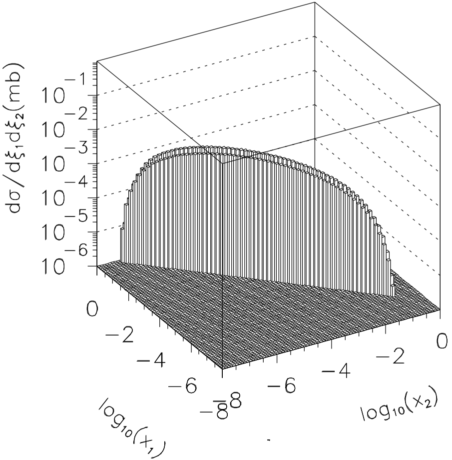
Explicitly:

$$y_Q = \log\left(\frac{x_Q\sqrt{s}}{\sqrt{\mathbf{k}^2 + m_Q^2}}\right), \; y_{\bar{Q}} = \log\left(\frac{x_{\bar{Q}}\sqrt{s}}{\sqrt{\mathbf{k}^2 + m_Q^2}}\right). \tag{23}$$

The rapidity difference Δy, and average rapidity $Y = (y_Q + y_{\bar{Q}})/2$ of quark and antiquark are

$$\begin{aligned} \Delta y &= y_Q - y_{\bar{Q}} = \log\left(\frac{x_Q}{x_{\bar{Q}}}\right) = \log\left(\frac{z}{1-z}\right), \\ Y &= \frac{1}{2}(y_Q + y_{\bar{Q}}) = \frac{1}{2}\log\left(\frac{x_Q x_{\bar{Q}} s}{\mathbf{k}^2 + m_Q^2}\right) = \frac{1}{2}\log\left(\frac{x}{x_{\mathbf{P}}}\right). \end{aligned} \tag{24}$$

First results



GJR GDF and Kutak-Staśto UGDF

$x_2 \sim 10^{-6}$ -- nonlinear effects

Figure:

First results

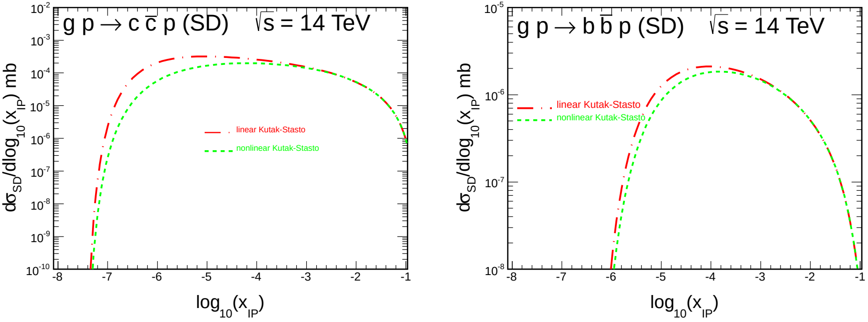


Figure: Absorptive effects have been included by multiplying by gap survival factor.

nonlinear effects for small $x_{\mathbb{P}}$

First results

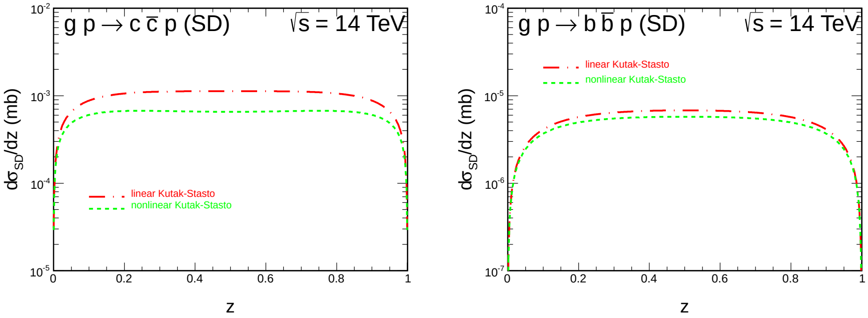


Figure: Absorptive effects have been included by multiplying the model cross section by gap survival factor.

First results

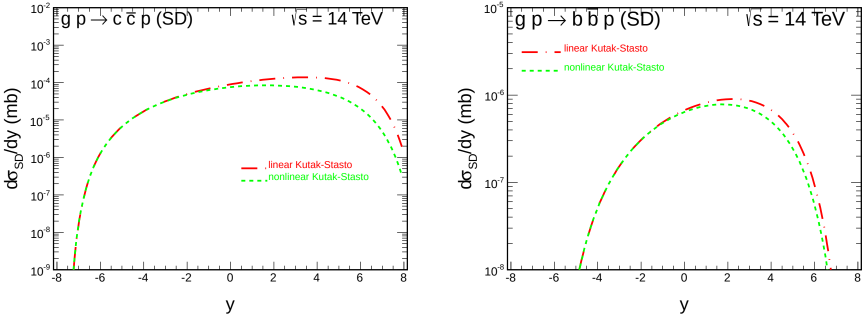


Figure: Absorptive effects have been included by multiplying by gap survival factor.

large y -- nonlinear effects

First results

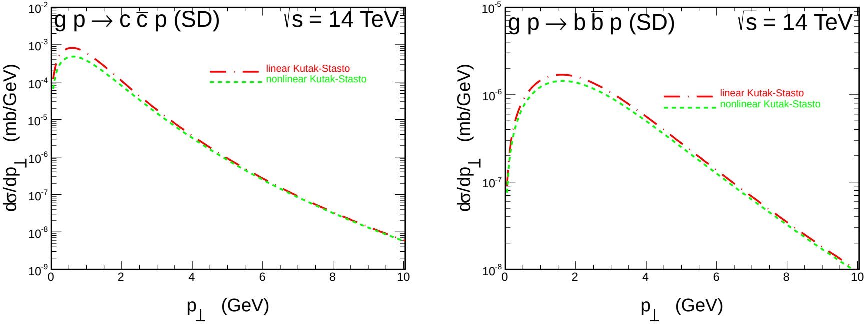
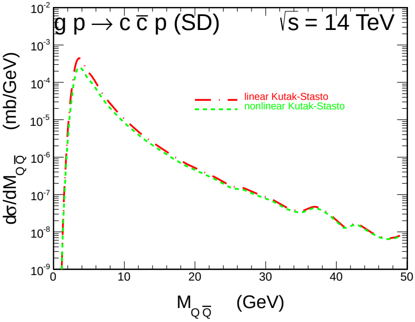


Figure: Absorptive effects have been included by multiplying by gap survival factor.

relatively sharp distributions, nonlinear effects at small p_t

First results



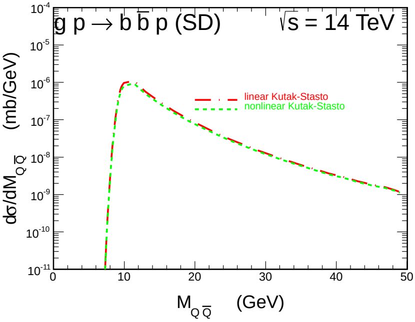


Figure: Absorptive effects have been included by multiplying by gap survival factor.

First results

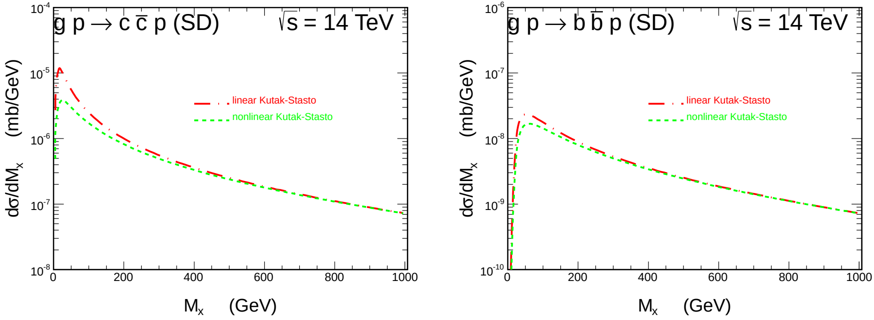


Figure: Absorptive effects have been included by multiplying by gap survival factor.

very slow decrease

First results, Ingelman-Schlein vs gluon dissociation

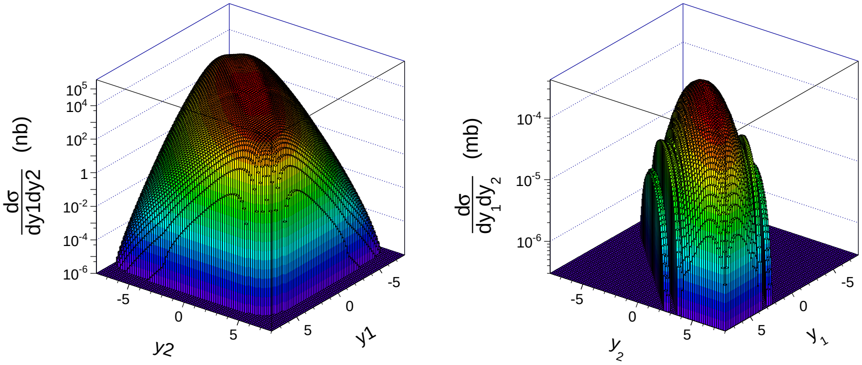


Figure: No absorptive effects.

Ratios, GD vs IS

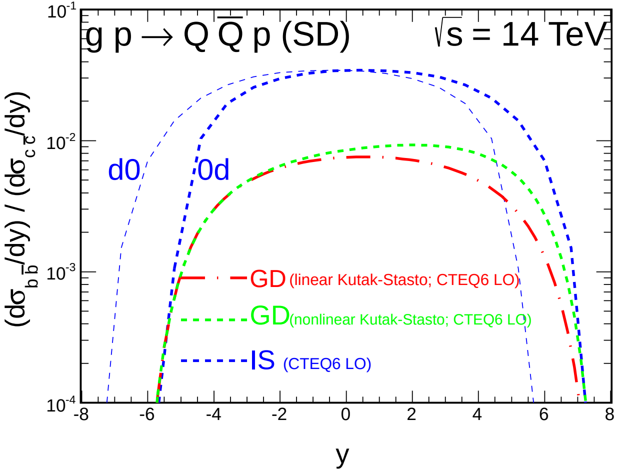


Figure:

Ratios, GD vs IS

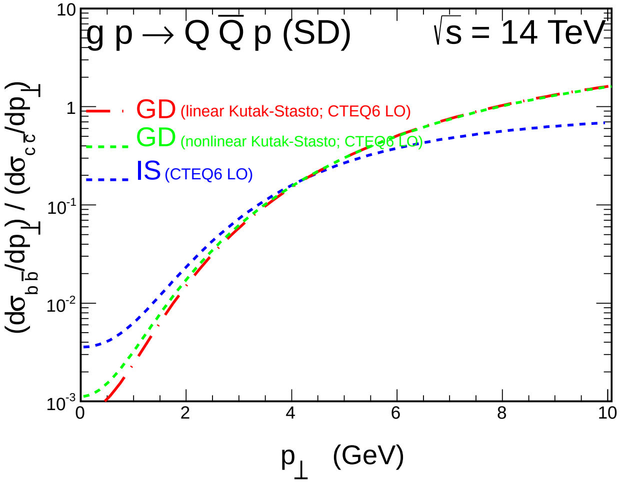


Figure:

Ratios, GD vs IS

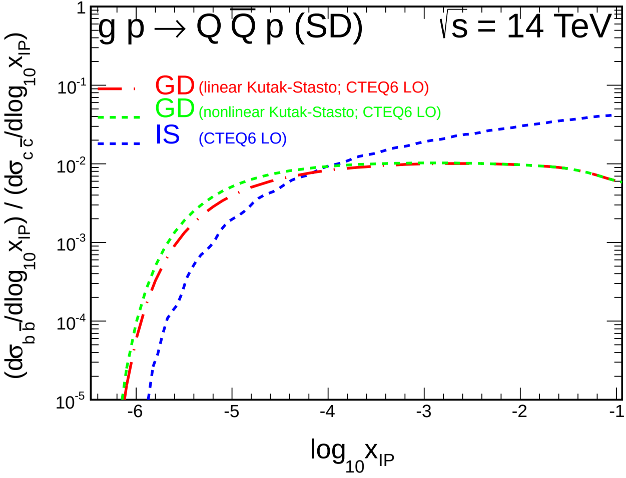


Figure:

Ratios,GD vs IS

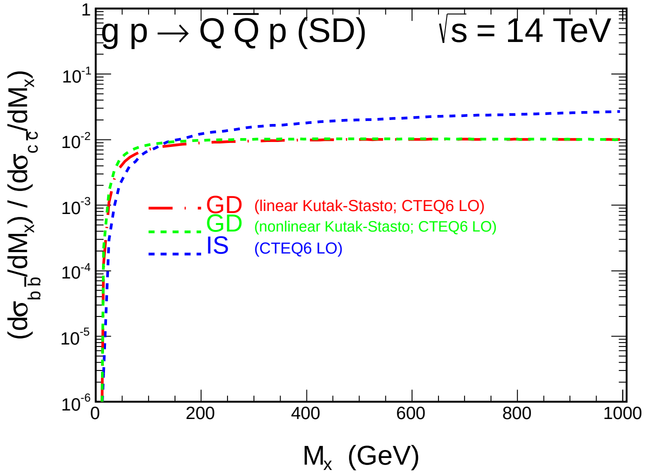
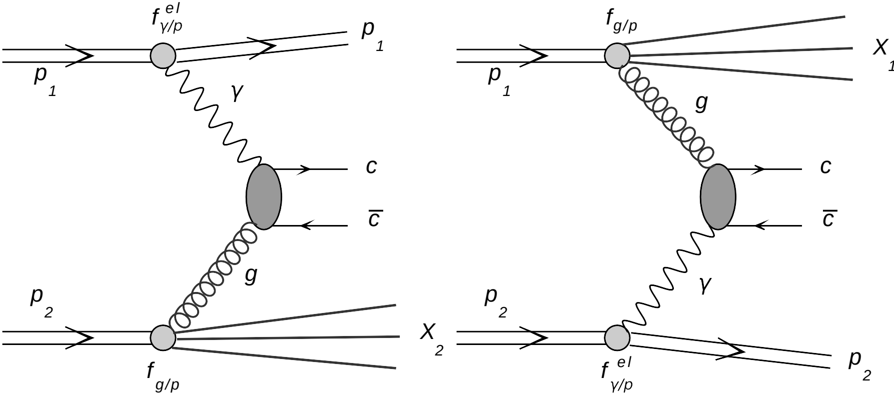
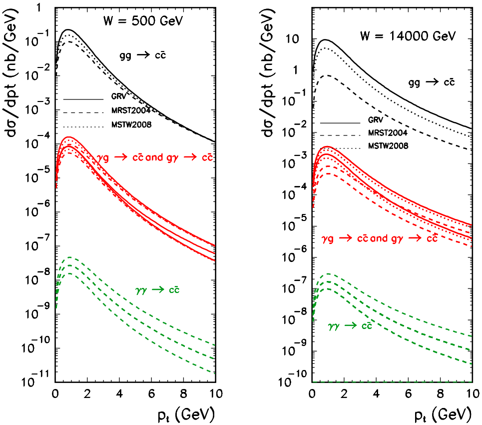


Figure:

Photon-induced processes



Photon-induced processes, results



Luszczak, Maciula, Szczurek, Phys. Rev. **D84** (2011) 4018

Summary and conclusions

- Amplitude for gluon dissociation into a pair of heavy quark and heavy antiquark was derived in the impact parameter and momentum space. Different result than in the literature.
- Corresponding hadronic cross section for single-diffractive $Q\bar{Q}$ production has been calculated.
- A comparison to the Ingelman-Schlein (resolved pomeron) has been made.
- Gluon dissociation cross section is much smaller than that for the resolved pomeron due to special topology and diagram cancellation.
- The ratios of the cross section for $b\bar{b}$ and $c\bar{c}$ have been calculated. The predictions are waiting for verification.
- Competition of diffractive mechanisms and photon-induced processes. It has to be studied more.